Mercury Strategy for the Bay-Delta Ecosystem: A Unifying Framework for Science, Adaptive Management, and Ecological Restoration

by

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EXECUTIVE SUMMARY

Ecosystem restoration and management of the San Francisco Bay and Sacramento-San Joaquin Delta are complicated by mercury contamination from historic mining sites in the Sacramento and San Joaquin river watersheds, the principal sources of fresh water for the Bay-Delta System. Mercury-enriched sediment now contaminates extensive downstream reaches of tributary streams and rivers, adjoining floodplains, and the Bay-Delta estuary. A challenge to scientists and managers involved with restoration of this ecosystem is to avoid increasing the exposure of biota to methylmercury, the highly toxic form that readily accumulates in exposed organisms and biomagnifies to high concentrations in fish and wildlife atop aquatic food webs. Indeed, it would be desirable to eventually decrease methylmercury exposure in this ecosystem to a level where wildlife, fishery resources, and human health are unaffected. The production of methylmercury via the microbial methylation of inorganic divalent mercury in the environment is a key process affecting methylmercury concentrations in biota at all trophic levels. Natural processes and human activities – possibly including ecosystem restoration projects – that alter the net production of methylmercury (i.e., methylation minus demethylation) can influence the abundance of methylmercury in the ecosystem and the associated exposure of resident biota and humans who consume fish and other aquatic biota from the ecosystem.

The overall goals outlined in the strategic plan for CALFED's Ecosystem Restoration Program for the Bay-Delta System are (1) to assist and recover at-risk native species, (2) to rehabilitate the Bay-Delta to support native aquatic and terrestrial biotic communities, (3) to maintain or enhance selected species for harvest, (4) to protect and restore functional habitat for both ecological and public values, (5) to prevent the establishment of additional non-native species, and (6) to improve or maintain water and sediment quality. Success in achieving most of these goals will hinge partly on the behavior and mitigation of mercury in the ecosystem, given that methylmercury contamination and exposure can adversely affect the health and reproductive success of native fish and wildlife, diminish the benefits derived from fisheries, degrade the quality of water and sediment, and pose health risks to humans.

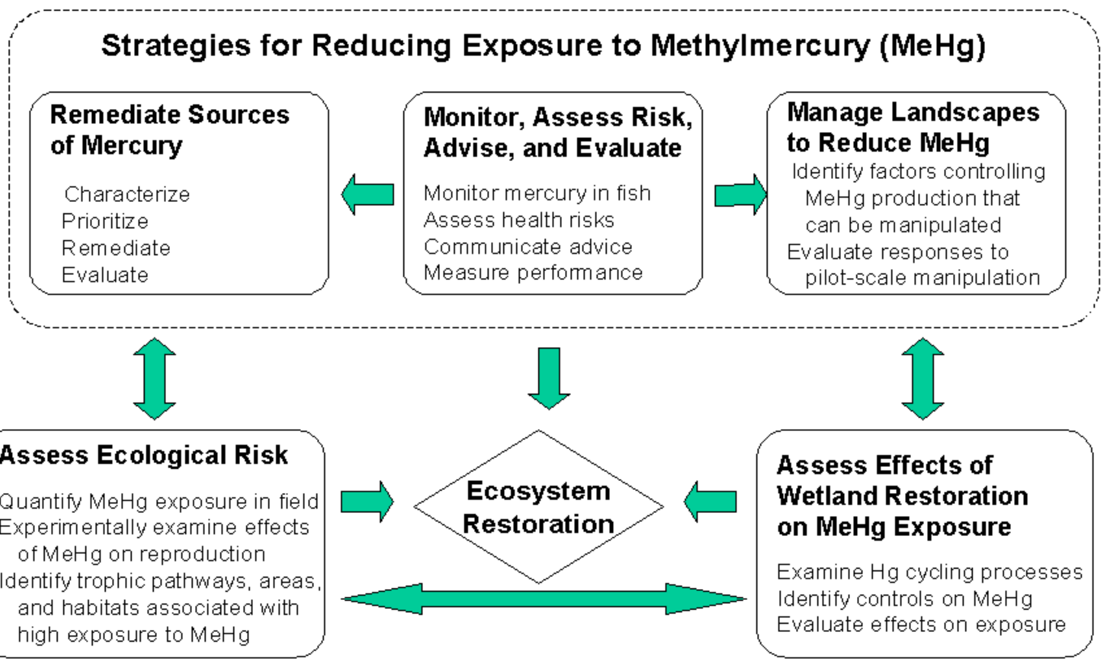
This document outlines a strategy for integrated mercury investigations linked to restoration and adaptive management of the San Francisco Bay-Delta ecosystem (defined as the combined watershed, Delta, and Bay). The goal of the mercury strategy is to provide a unifying framework for the integrated investigations needed to build a scientific foundation for ecosystem restoration, environmental planning, and the assessment and eventual reduction of mercury-related risks in the Bay-Delta ecosystem. The strategy was developed by a team of independent scientists with input obtained in two public workshops attended by resource managers, environmental planners, scientists, and other stakeholders from the region, as well as external technical experts. This document briefly describes the Bay-Delta ecosystem, summarizes our current knowledge of mercury contamination and cycling in the ecosystem, considers the potential influences of ecosystem restoration activities on mercury cycling and methylmercury exposure, describes the development of the strategy, recommends six interactive core components of a mercury program focused on the ecosystem, and provides guidance for management of that program. The document does not recommend specific projects for funding, although useful mechanisms for selecting projects and project teams are discussed. In short, the mercury strategy provides a cohesive framework for CALFED managers, partners, and participating scientists and offers guidance on certain, crucial aspects of an interdisciplinary mercury program.

Clear definition of the problem or problems affecting ecosystem or human health is an essential first step in adaptive management, an operational process being used in the CALFED Ecosystem Restoration Program in restoring the ecological health of the Bay-Delta ecosystem. In a toxicological sense, the primary problem with mercury in aquatic ecosystems can be defined as *biotic exposure to methylmercury*. It follows that the overall challenge to scientists and managers involved with ecological restoration in the Bay-Delta ecosystem is to *avoid increasing – and to eventually decrease – biotic exposure to methylmercury*. This challenge should provide a unifying sense of purpose for scientists, ecosystem managers, and other participants, as well as a unifying framework for adaptive management of this mercury-contaminated ecosystem.

The framework for the mercury strategy contains six core components. Each core component addresses one or more management goals and includes specific, supporting objectives pertaining to scientific activities (research and monitoring), management actions, or both. Management actions include source remediation, risk communication, ecosystem restoration, and landscape management. The six core components and their associated management goals are as follows.

Core Components	**Management Goals**
Quantification and evaluation of mercury and methylmercury sources	To identify mercury sources that contribute most strongly to the production and bioaccumulation of methylmercury
Remediation of mercury source areas	To identify remedial actions that can reduce loadings of mercury from sources to surface waters and decrease the exposure of aquatic biota to methylmercury
Quantification of effects of ecosystem restoration on methylmercury exposure	To document and understand the effects of ecosystem restoration in wetland and floodplain habitats on the production and bioaccumulation of methylmercury in the Bay-Delta ecosystem
Monitoring of mercury in fish, health-risk assessment, and risk communication	To protect human health by providing informed guidance for reducing dietary exposure to methylmercury in fish To provide a “performance measure” to gage methylmercury contamination of the Bay-Delta ecosystem during restoration
Assessment of ecological risk	To protect fish and wildlife from adverse effects of methylmercury exposure
Identification and testing of potential management approaches for reducing methylmercury contamination	To identify and evaluate potential landscape management approaches for reducing the production and abundance of methylmercury in the ecosystem, as well as the associated exposure of resident biota

The six core components are strongly interconnected. The interactions include linkages between scientific research and monitoring and linkages between scientific investigations and management actions. The linkages among the core components are illustrated below, where shaded arrows represent the flows of information and interactions needed to support decisions regarding both refinement of scientific investigations and adaptive management of mercury in the ecosystem. These linkages are utterly crucial for meeting the goals and objectives outlined for the strategy and for providing timely scientific input for adaptive management of mercury in the ecosystem. The evaluation of outcomes is also an important feature of the strategy.



This framework incorporates two approaches that have been applied for decades to reduce exposure to methylmercury: reduction of mercury loadings and monitoring of mercury in fish as a scientific foundation for providing fish-consumption advice. A third, largely untested approach, management of contaminated landscapes to decrease the *in situ* net production of methylmercury, should be evaluated as a potential means of reducing methylmercury contamination and exposure in this ecosystem.

In evaluating effects of ecosystem restoration on mercury cycling, we recommend that the highest priority be given to examining effects of restoration on (1) the bioavailability of inorganic mercury for methylation and (2) the microbial production of methylmercury. Mercury contamination of aquatic environments is widespread in the Bay-Delta ecosystem. We believe that changes in bioavailability or methylation rates have much greater potential to significantly increase methylmercury exposure in this ecosystem than do changes in the spatial distribution of total (mostly inorganic) mercury. Studies in other aquatic ecosystems have shown that stimulation of methylation can increase the abundance of methylmercury and its uptake in biota by 10- to 20-fold, even in lightly contaminated environments where no mercury was added.

The competitive Proposal Solicitation Package process used by CALFED is an appropriate mechanism for allocating scientific effort to all but one core component (monitoring). An interdisciplinary effort will be needed to implement this strategy and to apply the resulting information towards adaptive management of the Bay-Delta ecosystem. Requests for proposals should, therefore, encourage development of interdisciplinary proposals by multi-institutional teams of investigators. In addition to judging scientific merit and relevance to ecosystem management, the proposal review and selection process should critically assess the effectiveness of project teams, by considering team leadership, disciplinary composition, relevant experience, technical capabilities, and information transfer. Critical evaluation of the mercury problem in this ecosystem will be complicated by the spatiotemporal dynamics and complexity of the ecosystem, and project teams should contain the range of expertise needed to ensure defensible study design, analyses, and interpretation of data. It is recommended that, on average, about half of the team members on a project be "mercury specialists" and the remainder be scientists who bring other, essential expertise and knowledge on ecosystem processes, organismal biology, wetland ecology, sampling design, statistical analysis, modeling, or other pertinent applications. Project proposals should also demonstrate earnest commitments to provide timely information to ecosystem managers, to engage actively in the application of project results to adaptive management, and to participate substantively in the syntheses of results from multiple projects.

The establishment of a systemic monitoring program for mercury in fish is a high priority. The development and design of an effective monitoring program will require insightful leadership, input from managers and stakeholders, multidisciplinary technical guidance, and modest budgetary support. We recommend and have outlined a step-wise approach for development of a mercury monitoring program, which would incorporate input from scientists, managers, and end-users of the monitoring data along the way. Procedures for programmatic oversight of quality assurance should be in place at the onset of monitoring and other funded investigations to establish that the data emanating from multiple teams and laboratories are comparable and valid.

The transfer and sharing of information from mercury investigations should be actively facilitated, given the importance of rigorous interdisciplinary synthesis of results and timely provision of information for adaptive management. Effective mechanisms for rapid information transfer will be essential to ensure that interim data and information are available to facilitate timely information synthesis and application to management decisions. An annual workshop should be convened to provide a forum for sharing, discussion, and integration of interim results. Peer review by an external science panel should be a focal point of the workshop, providing constructive feedback at both the project and multi-project levels.

Mercury-polluted landscapes present an enormous challenge for ecosystem management. An integrated mercury program would catalyze essential advances in understanding of the cycling, effects, and remediation of this toxic metal and should enhance scientific understanding of the Bay-Delta ecosystem.

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I. INTRODUCTION

The mining of mercury and the use of mercury in gold mining have released large quantities of the metal to the environment of California since the mid 1800s (Alpers and Hunerlach 2000). Prolonged releases of mercury, including methylmercury, from historic mining sites can impact downstream environments for decades to centuries after mining operations cease (Lacerda and Salomons 1999, Ganguli et al. 2000, Rytuba 2000, Coolbaugh et al. 2002). In California and elsewhere, the transport of mercury-contaminated water and sediment from historic mercury- and gold-mining areas has contaminated aquatic environments and floodplains far downstream (Domagalski 1998, 2001, Ganguli et al. 2000, Rytuba 2000). These contaminated sites include the Sacramento and San Joaquin rivers, the Sacramento-San Joaquin Delta, and the San Francisco Bay. The Sacramento River watershed, the primary source of fresh water for the Bay-Delta, was a site of intensive historic mining for gold and mercury and is an important modern source of mercury and methylmercury for the Bay-Delta (Domagalski 2001, Choe and Gill in press, Choe et al. in press).

Concerns about mercury pollution stem largely from the potential adverse effects of dietary exposure to methylmercury, a highly toxic form that readily accumulates in biota and can biomagnify to harmful concentrations in organisms atop aquatic food webs (Mahaffey 2000, Clarkson 2002, Wiener et al. 2003). Documented consequences of methylmercury pollution include (1) direct adverse effects on the health and fitness of fish, wildlife, and humans, (2) contamination of fishery resources that diminishes their nutritional, cultural, socioeconomic, and recreational benefits, and (3) socio-cultural damage to indigenous peoples who had fished for subsistence (Mahaffey 2000, NRC Committee on the Toxicological Effects of Methylmercury 2000, Wheatley and Wheatley 2000, Clarkson 2002, Wiener et al. 2003). Nearly all of the mercury in fish is methylmercury (Grieb et al. 1990, Bloom 1992), and consumption of fish is the primary modern pathway of methylmercury exposure in humans (NRC Committee on the Toxicological Effects of Methylmercury 2000, Mahaffey 2000, Clarkson 2002). Dietary exposure to methylmercury can be substantial for predatory fish and wildlife atop aquatic food webs (Wiener et al. 2003), and recent studies suggest that the reproductive success of some nesting aquatic birds is being adversely affected by methylmercury exposure in the Bay-Delta ecosystem (Hoffman et al. 1998, Heinz 2002, Schwarzbach and Adelsbach 2002).

The historic contamination and continuing transport and loading of mercury to the Bay-Delta ecosystem have significant implications for its ecological restoration and management. Concentrations of methylmercury in food webs supporting production of fish and aquatic wildlife are strongly correlated with the supply of methylmercury (Hecky et al. 1991, Kelly et al. 1997, Gilmour et al. 1998, Paterson et al. 1998, Heyes et al. 2000, Wiener et al. 2003). Hence, the production of methylmercury in aquatic ecosystems via the microbial methylation of inorganic mercury (reviewed in Benoit et al. 2003) is a key process affecting methylmercury concentrations in aquatic invertebrates, fish, and wildlife (reviewed in Wiener et al. 2003). It follows that the array of natural processes, human activities, and disturbances affecting the rates of production and degradation of methylmercury on the landscape can markedly influence the methylmercury content of aquatic biota and the associated exposure of consumers of these biotic resources.

Wetlands, which are generally considered important sites of microbial methylation on the landscape, can be dominant sources of methylmercury for downstream waters (Hurley et al. 1995, St. Louis et al. 1996, Waldron et al. 2000, Domagalski 2001, Sellers et al. 2001). The restoration of wetlands, particularly in areas where the abundance of mercury in soils or sediments has been elevated by mining or other human activities, could accelerate the production of methylmercury and increase the contamination of aquatic biota (Naimo et al. 2000, Wiener and Shields 2000). In addition, flooding of vegetated wetlands or uplands, or fluctuating water levels during tidal cycles, could stimulate microbial methylation of inorganic mercury, increasing concentrations of methylmercury in water and biota (Hecky et al. 1991, Hall et al. 1998, Paterson et al. 1998, Bodaly and Fudge 1999, Bodaly et al. 2002).

This report presents a strategy for addressing key questions concerning the biogeochemical cycling and potential effects of mercury in the Bay-Delta ecosystem. The *goal* of the mercury strategy is to provide a holistic framework for integrated investigations needed to build a scientific foundation for ecosystem restoration, environmental planning, and the assessment and eventual reduction of mercury-related risks in the Bay Delta ecosystem.

II. THE SAN FRANCISCO BAY-DELTA ECOSYSTEM

The Ecosystem

The modern San Francisco Bay-Delta ecosystem can be described as three physiographic areas: the San Francisco Bay and its estuarine embayments, the Sacramento-San Joaquin River Delta, and the Sacramento and San Joaquin River watersheds that drain into the Delta. Conditions across this ecosystem range from the marine environment of central San Francisco Bay to high-gradient tributaries fed largely by snow melt in the Coast Ranges and the western slopes of the Sierra Nevada. The “Delta”, once an expansive area of tidal and non-tidal wetlands, lies at the convergence of the Sacramento and San Joaquin rivers (Figure 1).

The Sacramento and San Joaquin rivers together drain about 37 percent of California. The Sacramento River basin is the state’s largest (nearly 70,000 square kilometers), with annual runoff of about 27-billion cubic meters, about one-third of the total runoff in California and about 5 to 6 times that of the San Joaquin River basin (http://waterdata.usgs.gov/nwis/). The Sacramento River is a major source of drinking water for the state, as well as the principal source of irrigation water for agriculture in the Sacramento and San Joaquin valleys (Central Valley). The Sacramento River basin includes all or parts of five physiographic provinces: the Sacramento Valley, the Sierra Nevada, the Coast Ranges, the Cascade Range, the Klamath Mountains, and the Modoc Plateau. The northernmost area (Modoc Plateau) is a high desert plateau with cold snowy winters, moderate rainfall (about 30 cm), and hot dry summers. Other high-elevation portions of the basin (including the Cascade, Coast, and Sierra Nevada ranges) receive more precipitation (~ 50-100 cm per year) with melting winter snow yielding most of the spring and summer runoff.

The San Joaquin River basin, which drains the Central Valley from the south, is bounded by the Sierra Nevada to the east, the Coast Ranges to the west, and the Tehachapi Mountains to the south. The San Joaquin River basin is more arid than the Sacramento River basin, with hotter summers and milder winters. The San Joaquin River receives water from tributaries draining the Sierra Nevada and Coast Ranges, and except for streams discharging directly to the Sacramento-San Joaquin Delta, is the only surface-water outlet from this basin.

Figure 1. Map of the San Francisco Bay-Delta, which includes the San Francisco Bay and the delta of the Sacramento and San Joaquin rivers (source: CALFED Bay-Delta Program).

The modern San Francisco Bay can be characterized as an ecologically young, but extensively modified, estuarine ecosystem. The estuary was formed 15,000 to 18,000 years ago, when rising sea waters from glacial melting entered the Golden Gate, inundating what are now the major embayments of the San Francisco Bay (San Pablo Bay, Carquinez Strait, Suisan Bay, Grizzly Bay, Honker Bay), transforming a riverine system into an extensive and complex estuary (Atwater 1979). Together, the Sacramento-San Joaquin Delta and the embayments of San Francisco Bay form the largest estuary on the West Coast of the United States, with a combined area of about 3000 square kilometers. The Delta is estuarine through its lower end, but is almost completely influenced by tidal cycles. About 72 percent of the Delta land area is in agricultural production, which was engineered via a complex system of dikes, drainage ditches, irrigation diversions, pumps, and floodgates. This complex drainage pattern combined with a strong tidal currents create large tidal excursions, where distinct water parcels, with distinct chemical characteristics, can travel many miles on a given ebb or flood tide in patterns that are difficult to predict or anticipate. Freshwater inflows (excluding precipitation) to the Delta are mainly from the Sacramento River (about 75-80 percent), with most of this inflow during January to April.

Mining and Mercury

The mountain ranges that surround California's Central Valley and drain into the Sacramento and San Joaquin watersheds contain extensive mineral deposits. Discovery of gold deposits in the Klamath Mountains and Sierra Nevada stimulated the California Gold Rush in 1848, and an abundance of mercury – mined from deposits in the Coast Ranges – facilitated the rapid historic proliferation of gold-mining operations (Figure 2) that used the mercury-amalgamation process to extract gold (Alpers and Hunerlach 2000). Hundreds of hydraulic gold-placer mines operated on the east side of the Central Valley, where tens of millions of cubic meters of rock and earth were excavated annually by hydraulic mining. The resulting mining debris choked streams and rivers downstream of mining sites, and in some cases valleys were nearly filled with debris. About 100,000 metric tons of mercury were produced by mercury-mining operations in the Coast Ranges, and about 12,000 metric tons of this were used in gold mining in California, with annual losses at mine sites ranging from about 10 to 30 percent of the mercury used (Alpers and Hunerlach 2000). The effects of these mining activities are evident in the Bay-Delta estuary far downstream (Conomos et al. 1985). Consequently, mercury from a mineral belt associated with Cenozoic hydrothermal deposits in the Coast Ranges (Rytuba 1996) now contaminates environments extending from San Francisco Bay (Hornberger et al. 1999) to the Sierra Nevada and far beyond (Schuster et al. 2002).

The accumulation of contaminated debris from gold mining caused a notable loss of depth in parts of the San Francisco Bay (Nichols et al. 1986, Cappiella et al. 1999). In the past 50 years, however, the amount of additional sedimentation attributable to the Gold Rush has declined substantially, and further declines are predicted (Jaffee et al. 1998). All of the major rivers in the Sacramento River basin (Sacramento, Feather, American, Yuba) are impounded. The impoundments have decreased sediment export from the basin (Goals Project 1999), and the suspended sediment load of the Sacramento River has declined since 1960 (Krone 1996). Given that about 90 percent of the total mercury load to the Bay-Delta ecosystem from the Sacramento River is sediment borne (Foe 2002), it can be reasonably inferred that mercury loads have correspondingly declined and that future activities affecting sediment budgets could substantially

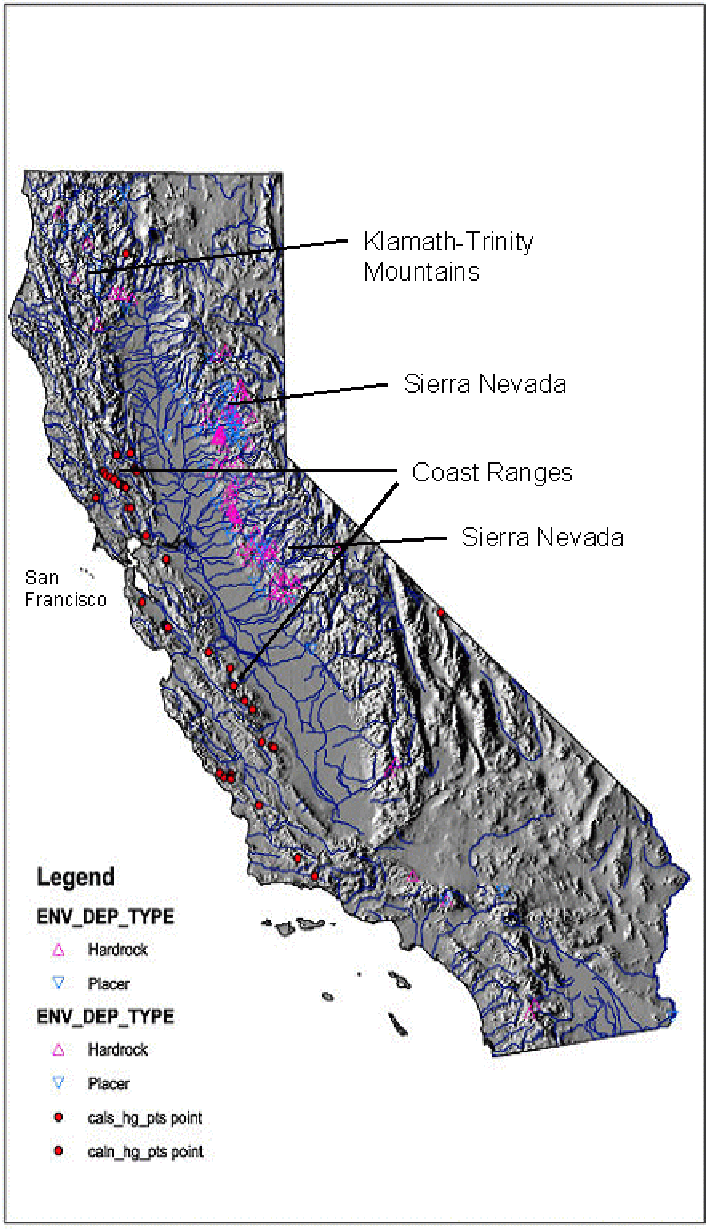

Figure 2. Locations of known mercury mines and gold mines in California (map provided by the U.S. Geological Survey).

affect mercury loadings. During 1955-1990, the estuary accumulated sediment, with estimated annual inflow of sediment averaging 6.03 million cubic meters (Krone 1996); an estimated 43 percent of this inflowing sediment was exported to the ocean and 52 percent accumulated in the estuary (Krone 1996).

Mercury Cycling

The mercury problem in the Bay-Delta estuary is extremely complex and somewhat unusual. Most industrial point sources of mercury in North America have been curtailed, and much of the scientific attention now focuses on mercury contamination associated with atmospheric emissions and deposition. The Bay-Delta ecosystem, in contrast, receives substantial mercury from former mine sites and historically contaminated waterways. Mercury concentrations in 75-cm striped bass (*Morone saxatilis*) from the Bay and Delta range from 0.3 mg/kg to greater than 1.5 mg/kg wet weight (California State Department of Public Health 1971, Fairey et al. 1997, Davis et al. 2002). In comparison, striped bass of the same size from the Chesapeake Bay, the largest estuary on the East Coast of the United States, range from 0.1 to 0.5 mg/kg (Gilmour and Riedel 2000). Atmospheric deposition is the primary modern source of mercury to the Chesapeake Bay watershed (Mason et al. 1997*a*, 1997*b*).

Understanding of mercury cycling in the Bay-Delta ecosystem has advanced markedly in the last 3 years, as findings of recent investigations have become available (Stephenson et al. 2002). Figure 3 is a conceptual model of mercury transport and cycling in the San Francisco Bay-Delta ecosystem, derived from a synthesis of recent investigations. Historically, mine sites in the Sierra and Coast ranges have been the major anthropogenic sources of mercury to the Bay-Delta ecosystem, and these loadings would have been mostly sediment-borne. Analyses of recent samples from former mercury-mining sites and thermal springs have provided information on the magnitude and speciation of mercury exported from the sites (Ganguli et al. 2000, Rytuba 2000, Churchill and Clinkenbeard 2002). Some of the mine sites in the Cache Creek watershed, an important source of mercury in the Sacramento River basin (Domagalski 2001), have been characterized recently (Churchill and Clinkenbeard 2002, Suchanek et al. 2002), including assessments of erosional and aqueous loads of mercury downstream. Mercury is transported via erosion from Cache Creek mine sites primarily during the rainy season (Churchill and Clinkenbeard 2002), although more sampling is needed during storm events to quantify associated loads.

The forms of mercury eroding from mining sites in the Coast Range are mainly cinnabar and metacinnabar (Bloom 2002). These forms have low solubility under oxic conditions but can dissolve and become available for methylation in anoxic, sulfidic sediments (Benoit et al. 2001, Bloom 2002). Organic matter can also solubilize cinnabar (Ravichandran et al. 1998, Haitzer et al. 2002), although the effect of this dissolution on methylation has not been determined. Thermal springs are lesser sources of mercury in the Cache Creek watershed than abandoned mine sites, but are much greater sources of sulfate (Churchill and Clinkenbeard 2002). Sulfate from thermal springs and other sources can stimulate the methylation of inorganic, divalent mercury by increasing the activity of mercury-methylating, sulfate-reducing bacteria (Rytuba 2000, Benoit et al. 2003). The release of mercury from gold mines in the Sierra, and the form of mercury in those mines has been less well studied, although initial observations indicate that it may be more readily methylated (Heim et al. 2002, Gill 2002, Slotten et al. 2002*a*). Information

(Figure 3 to be inserted here)

Figure 3. Conceptual model based on present understanding of mercury sources and cycling in the San Francisco Bay-Delta ecosystem (modified from Alpers and Hunerlach 2000 and Stephenson et al. 2002).

on the mobility and bioavailability (for methylation) of mercury exported from mine sites would be useful for selecting potential sites for remediation.

Spatial and temporal patterns in concentrations of total mercury and methylmercury in water and biota were recently characterized for the Cache Creek watershed (Domagalski 2001, Domagalski et al. 2002, Slotten et al. 2002*b*, Suchanek et al. 2002), yielding useful data for assessing the efficacy of future restoration efforts there. However, baseline information on concentrations of mercury and methylmercury in stream-bank and bed sediments downstream from the mine sites is comparatively sparse. Yet spatial patterns in the concentrations and speciation of mercury in mine drainage, stream-water, and sediment below mine sites clearly shows that methylmercury is being produced in such zones (Ganguli et al. 2000, Rytuba 2000, Bloom 2002).

Quantification of the relative importance of mercury sources to the Bay-Delta estuary has only recently been attempted. Analyses of sediment cores show that mercury-contaminated sediments were being deposited in San Pablo Bay (northern San Francisco Bay) between 1850 and 1880, probably from incoming debris from hydraulic gold mining (Hornberger et al. 1999). Moreover, maximum concentrations in the cores were 20 times the concentrations in sediments deposited before 1850. Domagalski (2001) identified the Cache Creek watershed and unknown sources in the upper Sacramento River basin as the major source regions for mercury to the Bay-Delta estuary. An initial mercury budget constructed by Foe (2002) shows that both the Sacramento and San Joaquin rivers, as well as eroding contaminated sediments in Suisun Bay, are present sources of mercury to the Bay-Delta.

Historically contaminated sediments, whose present distribution extends from small streams below mine sites through the Delta and San Francisco Bay, are sources of residual mercury from historic mining operations. The modern distribution of contaminated sediments has been partially described, and recent surveys have provided significant new information on the abundances of mercury and methylmercury in Delta sediments (Cappiella et al. 1999, Heim et al. 2002, Slotten et al. 2002*a*). Gill (2002), who estimated fluxes from Delta sediments, found that sediment-water exchange of total mercury and methylmercury rivaled external riverine sources during low-flow conditions, whereas external sources dominated during high flow. There were large temporal and spatial variations in estimated sediment-water exchanges of total mercury and methylmercury in the Delta in Gill's study. Mercury movement via bed load and sediment transport is difficult to quantify, but merits attention. Rigorous assessments of the contribution of contaminated sediments to overall budgets for mercury and methylmercury, with emphasis on active biogeochemical pools that contribute methylmercury to the benthic and pelagic food webs, are urgently needed.

Inputs of mercury via atmospheric deposition are small relative to land-based sources in the Bay-Delta ecosystem. In the Cache Creek watershed, mercury loading from mines sites far exceeds atmospheric deposition (Churchill and Clinkenbeard 2002), assuming that local emission and re-deposition is not large, an assumption that has not been tested. Moreover, the input of mercury from atmospheric deposition to the entire watershed appears to be less than the loadings from the Sacramento and San Joaquin rivers. Retention of atmospherically deposited mercury in watersheds is usually substantial (Hurley et al. 1995, Mason et al. 1997*a*, Lorey and Driscoll 1999), suggesting that non-atmospheric sources should dominate mercury loading to aquatic environments in this ecosystem. Mercury deposition rates have been measured for only a small part of the watershed (Tsai and Hoenicke 2001), however, and retention factors for mercury deposited in the watershed are unknown. The availability of inorganic mercury for methylation can vary greatly (Benoit et al. 1999*a*, 2001, Bloom 2002), and newly deposited mercury may be much more reactive than mercury that has been residing in the ecosystem (Hintelmann et al. 2002). The relative bioavailability of mercury derived from atmospheric deposition vs. residual mercury from mining sources is an important information gap – one that hinders the confirmation of mercury sources contributing to internal production of methylmercury in this ecosystem.

The internal cycling of mercury and methylmercury within the ecosystem is only beginning to be understood. The dominant loss terms for mercury in the Bay-Delta ecosystem, based on the present state of knowledge, are sedimentation and burial, loss to agricultural fields, export to the ocean, export to southern California, and evasion to the atmosphere (Figure 3). The relative importance of each of these fluxes in this ecosystem is poorly understood. Mercury and methylmercury behave non-conservatively across the estuarine salinity gradient (Choe and Gill in press, Choe et al. in press), with apparent mercury sources and methylmercury sinks in the estuary. Particulate mercury is the dominant phase in the estuary, and much of the filter-passing mercury is associated with colloids. Roughly half of the methylmercury in the estuary is associated with particles, and like mercury, much of the filter-passing methylmercury is associated with colloids. Measurement of partition coefficients suggests that methylmercury is preferentially associated with colloidal material relative to particles. These findings highlight the importance of organic matter in the cycling of mercury and methylmercury and have implications for mercury transport and methylation in the estuary.

Methylmercury is produced primarily by sulfate-reducing bacteria (Compeau and Bartha 1985, Gilmour et al. 1992, Pak and Bartha 1998, King et al. 2001), and the most important sites of microbial methylation in the Bay-Delta ecosystem are expected to be oxic-anoxic interfaces in sediments, wetlands, and seasonally inundated, vegetated habitats (St. Louis et al. 1994, Hurley et al. 1995, Kelly et al. 1997, Gilmour et al. 1998). Within the Delta, marshes seem to be more significant sites of methylmercury production than open-water sediments. Marshes, which have higher concentrations of methylmercury and higher methylation potential than do sediments in open-water areas (Heim et al. 2002, Slotten et al. 2002*a*), can export methylmercury via tidal currents (Gill 2002). Methylmercury can be transported from the site of methylation by several processes, including resuspension of bed sediments, diffusive and advective (e.g., tidal) solute fluxes, hydrologic transport with sediment or colloids, and uptake into mobile aquatic biota. Methylmercury can be lost by the processes of microbial demethylation, photodemethylation, burial in deposited sediment, and emigration or harvest of contaminated biota. Benoit et al. (2003) have reviewed current understanding of methylation and demethylation processes.

The distribution of methylmercury in open-water sediments in the Delta has been recently studied (Heim et al. 2002, Gill 2002, Slotten et al. 2002*a*). There is less information for marshes, diked islands, agricultural lands, and seasonally flooded areas, and budgets for the major sources and sinks of methylmercury within the Delta and the ecosystem remain poorly constrained. The relative rates of net methylmercury production across the complex mosaic of habitats in the Bay-Delta ecosystem are not well known. Methylmercury is being produced and bioaccumulated to high concentrations in streams near mine sites, where methylation probably occurs in mine wastes (calcines) and stream sediment (Rytuba 2000, Ganguli et al. 2000, Slotten et al. 2002*b*). Methylation in Delta marshes and submerged sediments, which has been quantified to some extent, exhibits substantial spatial variation (Gill 2002, Slotten et al. 2002*a*). Seasonality of methylmercury accumulation in sediments is apparent, with maxima mainly during the warmest temperatures, as noted in other ecosystems (Ramlal et al. 1993). Sediments appear to be a net source of methylmercury to the water column (Gill 2002).

Methylmercury concentrations and methylmercury as a percentage of total mercury are generally lower in the central Delta than at the periphery, near the major inflows to the Delta (Heim et al. 2002, Slotten et al. 2002*a*). Stephenson et al. (2002), who employed a mass balance approach, suggest that the central Delta is a sink for methylmercury, due to photodemethylation or storage via bioaccumulation. Slotten et al. (2002*a*) suggest that inorganic mercury newly delivered from upstream sources is more readily methylated and bioaccumulated than inorganic mercury stored in the central Delta. Marshes in the central Delta marshes may have high microbial methylation activity, yet inorganic mercury in the marshes may have relatively low bioavailability. Such questions will need to be addressed to understand sources of methylmercury in the ecosystem.

The rates of methylation in this ecosystem will be influenced by the bioavailability of inorganic mercury to methylating bacteria, the concentration and form of inorganic mercury, and the distribution and activity of methylating bacteria. Studies to date suggest that the bioavailability of inorganic mercury in the Bay-Delta ecosystem varies with the source and that the rate of methylation varies in time and space. There is a significant relation between the abundances of total mercury and methylmercury across ecosystems, but the concentration of inorganic mercury accounts for little of the variation in methylmercury production when data for multiple ecosystems are combined (Benoit et al. 2003).

Ambient concentrations of methylmercury provide an integrative measure of the impact of all the processes influencing the abundance of methylmercury, such as loading, flux, methylation, and demethylation. A quantitative model for methylmercury production across habitats in the Bay-Delta ecosystem would be useful for planning restoration strategies and should be a long-term goal of research. The next phase of mercury investigations in the Bay-Delta ecosystem should seek to understand the relative rates of methylmercury production across habitat types and salinity gradients, as well as the processes that contribute to differences in the abundance of methylmercury among habitats. Mercury studies in the Bay-Delta ecosystem should move from the descriptive phase into the mechanistic phase. Although the descriptive phase is not complete, this change is appropriate given that an understanding of controlling processes will be needed to move toward the desired predictive phase. Continuing work should link process-based studies to descriptive studies, monitoring, and restoration activities.

Ecological Status of the Bay-Delta

In the last 150 years, the Bay-Delta estuary has been modified greatly by human activities, including the diking and filling of wetlands, the reduction of freshwater inflow by more than half, the introductions of exotic species, and substantial anthropogenic inputs of nutrients, sediments, and potentially toxic contaminants (Nichols et al. 1986, van Geen and Luoma 1999). The area of tidal wetlands, for example, declined 95 percent, from 2200 square kilometers before 1850 to about 125 square kilometers in 1986 (Nichols et al. 1986).

The estuary is a spatially variable and temporally dynamic ecosystem, exhibiting biological change and pronounced variation in ecological structure and function on time scales ranging from diurnal to decadal (Cloern 1996, Jassby et al. 2002). Primary production in the Delta, which is rarely nutrient limited, is highest in the spring, much lower in summer, and lowest in winter and autumn (Jassby et al. 2002). During 1975-1995, primary production in the Delta declined 43 percent and varied as much as 3-fold between successive years (Jassby et al. 2002). The abundances of several species of native resident fish and zooplankton have decreased in recent decades, while abundances of several exotic invaders have increased (Nichols et al. 1986, Carlton et al. 1990, Bennett and Moyle 1996, Kimmerer and Orsi 1996, Orsi and Mecum 1996, Matern et al. 2002). The declines in native fish and zooplankton may be caused partly by the decrease in primary production, given that particulate organic matter from internal phytoplankton production is the dominant food supply for the Delta's planktonic food web (Sobczak et al. 2002).

Trophic pathways in the estuary have been strongly influenced by exotic species, particularly the Asian clam *Potamocorbula amurensis*, which has contributed to decreased primary production and food limitation (Kimmerer and Orsi 1996, Orsi and Mecum 1996, Jassby et al. 2002). This euryhaline bivalve invaded the Bay in 1986 and in 2 years had spread throughout the estuary (Carlton et al. 1990, Nichols et al. 1990). The clam feeds on phytoplankton (Canuel et al. 1995) and has altered trophic pathways in the estuary by diverting much of the primary production from the pelagic to the benthic food web (Alpine and Cloern 1992).

The effects of the observed dynamics in primary production and trophic pathways on the food-web transfer and compartmentalization of methylmercury in this ecosystem are not known. Given that biota in upper trophic levels obtain methylmercury almost entirely from dietary uptake, an understanding of their exposure to this toxic metal will hinge in part on a knowledge of trophic pathways and ecological processes supporting their production.

III. THE CALFED ECOSYSTEM RESTORATION PROGRAM

The mission of the CALFED Bay-Delta Program is to develop a long-term, comprehensive plan for restoring the ecological health and improving water management for beneficial uses of the Bay-Delta ecosystem. The Ecosystem Restoration Program is the principal CALFED program involved with restoring the ecological health of the Bay-Delta ecosystem. The restoration goals in the Ecosystem Restoration Program's strategic plan are (1) to assist and recover at-risk native species, (2) to rehabilitate the Bay-Delta to support native aquatic and terrestrial biotic communities, (3) to maintain or enhance selected species for harvest, (4) to protect and restore functional habitat for both ecological and public values, (5) to prevent the establishment of additional non-native species, and (6) to improve or maintain water and sediment quality (CALFED Bay-Delta Program 2000*a*). The Ecosystem Restoration Program applies an adaptive management approach to restoration, along with rigorous external review.

Success in achieving most of the Ecosystem Restoration Program's strategic goals will depend in part on the behavior and mitigation of mercury in the ecosystem. For example, the reproductive success of some native birds may be adversely affected by methylmercury exposure in parts of the ecosystem (Schwarzbach and Adelsbach 2002, Heinz 2002), and mercury contamination of fish (May et al. 2000, Thompson et al. 2000, Davis et al. 2002) can diminish some of the benefits derived from recreational fisheries. The reproductive success of fish can be greatly reduced by methylmercury exposure (Latif et al. 2001, Hammerschmidt et al. 2002, Wiener et al. 2003, M.B. Sandheinrich, University of Wisconsin-La Crosse, La Crosse, Wisconsin, personal communication), but reproductive effects of methylmercury on fish inhabiting the Bay-Delta ecosystem have not yet been examined. The quality of sediment and water in an ecosystem are clearly degraded if methylmercury is being bioaccumulated to levels that harm or otherwise devalue fish, shellfish, and wildlife.

A number of planned remedial and restoration activities in the Bay-Delta ecosystem may alter the production and bioaccumulation of methylmercury. Remedial actions at mercury source areas, such as mine sites, could reduce mercury loadings and methylmercury exposure. There is strong evidence that the export of mercury from historic mercury- and gold-mining sites causes significant contamination of biota downstream (May et al. 2000, Slotten et al. 2002*b*). Mercury loads from a number of mine sites have been estimated, and erosion control has been identified as the best restoration method for mercury in the solid phase (Churchill and Clinkenbeard 2002).

The selective remediation of contaminated bed sediments and stream banks may also reduce mercury loadings. The contribution of the mercury-contaminated sediments that are distributed throughout much of the Bay-Delta ecosystem to the methylmercury accumulated by biota is poorly understood. Mitigation activities at some contaminated sites may be useful, but more information on the contribution of contaminated stream beds and overbank sediments to the production and bioaccumulation of methylmercury, as well as current mercury loadings, would be desirable.

The effects of certain ecosystem restoration activities on the net production and bioaccumulation of methylmercury should be evaluated. Restoration could alter a variety of environmental variables that influence mercury cycling, methylation, demethylation, and bioaccumulation. Such variables include mercury loadings, habitat type, hydroperiod, oxic-anoxic boundaries in water and sediment, microbial activity, temperature, water chemistry, trophic status, and food-web structure. The relative influence of many of these factors on the production and bioaccumulation of methylmercury remains poorly quantified (for recent reviews, see Benoit et al. 2003, Wiener et al. 2003). The general types of restoration activities considered most likely to affect mercury cycling and methylmercury exposure include wetland restoration, restoration of seasonal floodplains, channel reconstruction, and dam removal. Examples of potential linkages between restoration activities and mercury cycling are illustrated below.

Wetland restoration and inundation of floodplains: Potential changes in the extent of methylmercury-producing habitat and in food-web structure. Wetland habitats are known to support high rates of microbial methylation (St. Louis et al. 1994, Gilmour et al. 1998, King et al. 1999), and initial data show that some Delta marshes produce and export methylmercury (Gill 2002, Slotten et al. 2002*a*). However, wetland and floodplain habitat varies greatly across the salinity gradient in the estuary, and little is known about the relative rates of methylmercury production and export across these habitat types. Shallow sediments and seasonally flooded soils are also potentially important sites of methylmercury production (Bodaly et al. 2002). Habitat changes resulting from wetland restoration and seasonal floodplain inundation could also influence food-web structure, affecting the biomagnification of methylmercury and exposure of organisms atop aquatic food webs (Wiener et al. 2003).

Channel reconstruction: Potential changes in bioavailability of mercury. Inventories of mercury are large in riverine sediments and overbank soils in parts of the Bay-Delta ecosystem. That mercury, however, may not be readily available for methylation, either because it is not physically located in zones of active methylation or because it has undergone diagenesis to forms with low solubility or low bioavailability for methylation. Disturbance of such contaminated sediments may increase the bioavailability of in-place mercury for methylation.

Steelhead and chinook salmon habitat restoration: Potential affects on mercury cycling. The removal of dams or other physical modifications of rivers can affect the transport, distribution, and transformations of sediment-associated mercury. The Upper Yuba River Studies Program, funded by CALFED, is evaluating the long-term biological, environmental, and socio-economic feasibility of introducing wild chinook salmon and steelhead trout to the Upper Yuba River Watershed. The fate of mercury in gold-mining debris accumulated above the Englebright Dam (a barrier to fish migration), the loading of mercury downstream, and the bioaccumulation of methylmercury in fish are key issues being examined in that Program (see Attachment F, Water Quality Presentation, at http://www.nasites.com/pam/yuba/documents.asp).

The risk of negative effects on the resource is inherent in resource management and cannot be eliminated entirely. Ecological restoration in a mercury-contaminated ecosystem – particularly the restoration of wetlands – could affect methylmercury production, increasing methylmercury contamination of food webs and exposure of biota.

IV. Development of the Mercury Strategy

Development of a mercury strategy was prompted by the recognized need for an integrated, systemic framework for addressing key management and scientific questions concerning the sources, biogeochemical cycling, effects, and mitigation of mercury in the Bay-Delta ecosystem. It was also recognized that critical evaluation of the effects of ecosystem restoration on mercury cycling and methylmercury exposure would require an integrated approach in an ecosystem of such large scale, dynamic character, and complexity.

Programmatic Guidance

The CALFED Science Program provided the following guidance regarding the mercury strategy. First, the strategy should include recommendations concerning (1) integrated monitoring of mercury in fish to assess risks to human health and wildlife, (2) holistic investigations that are systemic or process oriented, and (3) locally focused investigations, including remediation at mine sites. Second, the total cost of implementing the strategy should not exceed \$7 million to \$10 million per year. Third, the strategy should have a duration of 4 years.

In developing the strategy, we have also provided a framework conducive to adaptive management, an iterative learning and management approach used in CALFED programs to critically evaluate management actions and to apply both expert advice and the results of research and monitoring to future management actions (Jacobs et al. 2003). The strategy links monitoring and process-oriented research to restoration projects and remedial actions to provide information that can be applied to adaptive management of mercury as restoration progresses. The inclusion of science-based performance measures related to methylmercury exposure and associated risks is, therefore, an important feature of the mercury strategy.

Unifying Themes for a Science and Management Agenda

Clear definition of the problem(s) affecting ecosystem or human health is an essential first step in an adaptive management process (Johnson 1999*a*). In a toxicological sense, the primary problem with mercury in the Bay-Delta and other aquatic ecosystems can be defined as *biotic exposure to methylmercury*. It follows that the overall challenge to scientists and managers involved with ecological restoration in the Bay-Delta ecosystem is to *avoid increasing – and to eventually decrease – biotic exposure to methylmercury*. Success in meeting this substantial challenge will require rigorous interdisciplinary investigations and strong linkages between science and management. Moreover, the themes should provide a unifying sense of purpose for participating scientists, ecosystem managers, and other participants, as well as a unifying framework for adaptive management of this mercury-contaminated ecosystem.

Public Input

Two workshops were convened to review pertinent information on the Bay-Delta ecosystem and to obtain public input on the strategy. The first workshop, held on 16-17 September 2002, was devoted largely to a final review of the CALFED project titled "Assessment of Ecological and Human Health Impacts of Mercury in the Bay-Delta Watershed" (Appendix 1). That 3-year project examined patterns of mercury contamination in source areas, sediments, water, fish, and wildlife in the Bay-Delta watershed. The workshop, which had 87 attendees, also included presentations and discussions concerning other ongoing or planned studies of mercury in the Bay-Delta ecosystem and the first public discussion of the mercury strategy.

The second workshop, held on 8-9 October 2002, included (1) an assessment of the state of our knowledge regarding the cycling of mercury in the Bay-Delta and other aquatic ecosystems, (2) the identification of key management questions and goals pertaining to mercury in the Bay-Delta ecosystem, (3) the identification of critical information gaps concerning mercury in the ecosystem, (4) a discussion of potential linkages between ecological restoration projects and mercury cycling in the basin, and (5) a discussion of priority goals and objectives for mercury investigations (Appendix 2). This workshop, which had 93 attendees (Appendix 3), focused on obtaining input from environmental planners, resource managers, scientists, and the public. A series of breakout-group sessions served as the primary pathway for obtaining topical input from workshop participants (Appendix 4).

V. CORE COMPONENTS OF A MERCURY PROGRAM

The framework for the mercury strategy contains six core components. Each core component addresses one or more management goals and includes specific, supporting objectives pertaining to scientific activities (research and monitoring), management actions, or both. Management actions include source remediation, risk communication, ecosystem restoration, and landscape management. The six core components and their associated management goals are as follows.

Core Component	Management Goal(s) Addressed
1. Quantification and evaluation of mercury and methylmercury sources	To identify mercury sources that contribute most strongly to the production and bioaccumulation of methylmercury
2. Remediation of mercury source areas	To identify remedial actions that can reduce loadings of mercury from sources to surface waters and decrease the exposure of aquatic biota to methylmercury
3. Quantification of effects of ecosystem restoration on methylmercury exposure	To document and understand the effects of ecosystem restoration in wetland and floodplain habitats on the production and bioaccumulation of methylmercury in the Bay-Delta ecosystem
4. Monitoring of mercury in fish, health-risk assessment, and risk communication	To protect human health by providing informed guidance for reducing dietary exposure to methylmercury in fish To provide a “performance measure” to gage methylmercury contamination of the Bay-Delta ecosystem during restoration
5. Assessment of ecological risk	To protect fish and wildlife from adverse effects of methylmercury exposure
6. Identification and testing of potential management approaches for reducing methylmercury contamination	To identify and evaluate potential landscape management approaches for reducing the production and abundance of methylmercury in the ecosystem, as well as the associated exposure of resident biota

This framework incorporates two widely used approaches for reducing exposure to methylmercury: reduction of mercury loadings and monitoring of mercury in fish as a scientific foundation for providing fish-consumption advice. A third, largely untested approach, management of contaminated landscapes to decrease the *in situ* net production of methylmercury, is also included and should be evaluated as a potential means of reducing methylmercury contamination and exposure.

The rationale and objectives for each core component are as follows.

1. Quantification and Evaluation of Mercury and Methylmercury Sources

Mercury loading is one of the key factors affecting the production and bioaccumulation of methylmercury in an aquatic ecosystem. Accordingly, a coordinated effort is needed to estimate loading rates of mercury (from all relevant sources) to the San Francisco Bay-Delta ecosystem and to assess the relative contributions of different sources of (total and methyl) mercury to methylmercury exposure. Recent literature has shown that atmospheric deposition is the dominant source of mercury in many aquatic ecosystems (Fitzgerald et al. 1998, Wiener et al.

2003). However, few studies have been conducted in ecosystems with the complex array of potentially important sources (e.g., watershed inputs, wet deposition, dry deposition, geothermal, nearby oceanic emissions, discharges from industry and publicly owned treatment works, and a human population exceeding 10 million) expected in the San Francisco Bay-Delta ecosystem.

A recent assessment of mercury loads (Foe 2002) has shown that watershed inputs of mercury from the Sacramento and San Joaquin rivers dominate the mercury budget to the Delta. Yet recent research has shown that the phase, redox status, and ligand chemistry of the various mercury sources can strongly influence the bioavailability of inorganic mercury to methylating bacteria (Benoit et al. 1999*a*, 1999*b*, 2001, Babiarz et al. 2001, Bloom 2002, Drexel et al. 2002, Choe et al. in press). Thus, a mass-accounting approach for total mercury may not necessarily identify the most important source(s) of total mercury from the standpoint of methylmercury production and exposure. The development of strategies for mercury-source assessment is further complicated by the recent discovery that "new" inorganic Hg(II) entering an aquatic ecosystem is more available for methylation (and bioaccumulation) than is "old" mercury present in sediments and soils (Hintelmann et al. 2002, D.P. Krabbenhoft, U.S. Geological Survey, Middleton, Wisconsin, unpublished data). Mercury investigations in the Bay-Delta ecosystem should consider the reactivity and availability of mercury from various sources for microbial uptake and subsequent methylation.

The *primary management goal* for this core component is to identify the mercury sources that contribute most strongly to the production and bioaccumulation of methylmercury. This goal should be supported by the following objectives.

(1) To quantify and inventory mercury pools in the Bay and Delta. A useful exercise in a mass-loading assessment is to consider fluxes in the context of the standing pools of the contaminant of interest. For total mercury, and in some cases for methylmercury, bed sediment is the ecosystem compartment with the largest inventory of accumulated mercury. This should be the case in the Bay-Delta, given the historic and continuing inputs of mercury-contaminated sediment. Existing information (e.g., Cappiella et al. 1999, Hornberger et al. 1999, Heim et al. 2002, Slotten et al. 2002*a*) could be used to estimate sedimentary inventories of total mercury and methylmercury, although the existing data may over-represent open-water sites relative to vegetated environments (Heim et al. 2002, Gill 2002, Slotten et al. 2002*a*) that deserve attention.

(2) To inventory mercury-contaminated sediments within the Sacramento and San Joaquin river watersheds that are susceptible to mobilization by erosion. Assessments in the Cache Creek Watershed, a mineralized and mercury-rich sub-basin of the Sacramento River basin, have provided a general inventory of mercury sources (natural deposits, geothermal sources, and mercury-mining wastes) and good estimates of mercury fluxes from major streams in the sub-basin to the Sacramento River. The Cache Creek watershed is a small fraction of the Sacramento River basin, however, and the remainder of the basin is poorly understood. Vast amounts of mercury (millions of kilograms) were lost during the Gold Rush at mine sites in the Sierra Nevada, yet we are unaware of comprehensive quantitative assessments of residual mercury at the mines, the down-slope piles of mining wastes, the downstream reservoirs, or the alluvial deposits in the Central Valley upstream of the Bay-Delta. Large-scale assessments of this type could be expensive to execute and require considerable funding. A well-designed and coordinated GIS-based approach is, therefore, recommended to derive "bounding estimates" of

remaining mercury inventories in the basins, with emphasis placed on mercury-contaminated sediments that could be mobilized by erosive processes. This type of information would greatly aid and facilitate the remedial efforts described in core component 2 below.

(3) To assess the significance of mercury loadings to the Bay-Delta from other sources. Initial estimates of loadings of total mercury and methylmercury to the Bay-Delta, made at the macro scale, showed (i) that external loadings of total mercury are dominated by riverine flow, most notably the Sacramento River, (ii) that a significant fraction of the total mercury flux through the Bay-Delta is derived from resuspension of contaminated sediment, and (iii) that there is a methylmercury sink in the Bay-Delta (Domagalski et al. 2002, Foe 2002, Gill 2002). Additional evaluations should include urban sources (runoff, landfills, and publicly owned treatment works), an expanded network of sites for monitoring mercury in wet deposition (Tsai and Hoenicke 2001), contributions from dry atmospheric deposition (particulate and reactive gaseous mercury), and internal recycling via processes such as sediment resuspension and deposition within the Bay-Delta.

(4) To identify current key sources and sinks of methylmercury in the Bay-Delta. Wetlands, bed sediments, and flooded soils are likely to be the main sources of methylmercury within the watershed. Gill (2002) and Slotten et al. (2002*a*) showed that wetland soils in the Delta often have higher concentrations of methylmercury than adjoining open-water sediments, and that wetlands can be sources of methylmercury to surrounding waters. Beyond that, the types of existing habitats that support high rates of methylmercury production have not been characterized. Methylmercury concentrations, as a percentage of total mercury, in sediments and soils can be used as a surrogate and integrator of net methylmercury production. Examination of tidal fluxes from different landscape types is another useful tool. Both process-based research and landscape-level models will be needed to address this goal.

(5) To estimate fluxes of total mercury and methylmercury in the tidally influenced Bay-Delta. Assessing mass fluxes within the Bay-Delta system will be an important, but enormously challenging effort because of the system's complex hydrodynamic flow regime (Monismith et al. 2002, Schoellhamer 2002). Sampling strategies for quantifying material fluxes in tidally influenced areas should be designed with input from hydrodynamic specialists familiar with the Bay-Delta estuary to prevent aliasing, the introduction of spurious, low-frequency signals in time-series data that can be introduced by tidal fluctuations.

(6) To evaluate the reactivity and bioavailability (for methylation) of mercury from different sources. Recent estimates (Foe 2002) suggest that mercury loads from riverine sources are about 20 to 40 times those from atmospheric deposition. However, larger differences in reactivity or bioavailability (to methylating bacteria) among mercury phases and species in the Bay-Delta are possible, and the relative importance of different mercury sources to formation of methylmercury cannot be ascertained with existing information. Phase and redox speciation of mercury, redox conditions, chemistry of the aqueous environment, sulfur and carbon availability and cycling, and microbial activity all play key roles in determining methylation activity in an aquatic setting (Benoit et al. 2003, Wiener et al. 2003). Initial evaluations in the Bay-Delta ecosystem suggest that the solid-phase chemistry (mineralogy, stoichiometry, grain size, and reactivity) of mercury in mine wastes and stream bed sediments is quite variable (Bloom 2002). It is, therefore, probable that mercury sources will differ in their potential for yielding methylmercury.

2. Remediation of Mercury Source Areas

The *overall management goal* of this core component is to identify remedial actions that can reduce loadings of mercury from sources to surface waters *and* decrease the exposure of aquatic biota to methylmercury. Large amounts of mercury-contaminated mining wastes and sediment are now widely distributed in watersheds that are up-gradient from the Bay-Delta. Information is now available for identifying candidate mercury-mine sites for remediation, based on the estimated total annual export of mercury from the sites. It is tempting to assume that the best approach to mitigate the mercury problem in the Bay and Delta is through reduction of mercury loads; however, the identification of optimal remedial actions will require a more complete understanding of the relative reactivity and bioavailability (for methylation) of mercury from different sources. An *optimal remedial action* is defined here as one that will reduce loadings of mercury from sources and concomitantly decrease the abundance of methylmercury in receptor aquatic environments down gradient from the source.

A stepwise approach for the planning, testing, and implementation of remedial actions at mercury-source areas is outlined below. The distribution, mercury masses, and susceptibility for erosive transport of mercury have been characterized for selected mine sites in the Cache Creek Basin (Churchill and Clinkenbeard 2002); therefore, it is recommended that initial remedial planning and pilot projects be focused there. With the availability of additional information, remediation should be considered for other contaminated areas. The overall management goal for this core component should be supported by the following objectives.

(1) To develop a ranking system for prioritizing source areas (mine sites, stream bed and alluvial deposits, and geothermal springs) for possible remediation. This ranking system should identify mercury sources where remediation would have the greatest potential for reducing biological exposure to methylmercury in down-gradient aquatic environments. Variables for inclusion in the ranking system could include potential for erosion of mercury-contaminated substrates, the speciation and reactivity of mercury at the source site, the size of potentially mobile mercury deposits, the proximity to down-gradient aquatic environments, the relative methylation potential of down-gradient environments, the value of biotic resources in down-gradient aquatic environments, the likelihood for success for any particular site, and cost-benefit considerations. These variables could initially be weighted equally, given that we cannot presently predict their relative influence on methylmercury exposure in down-gradient environments.

(2) To identify remedial strategies for reducing the mobilization of mercury to down-gradient environments. Initial emphasis should focus on containing solid and aqueous phases of mercury, although strategies for containment of mercury-rich deposits should be general in nature and seek to minimize volatilization to the atmosphere. Control of erosion should be the main remedial method for containing solid-phase mercury (Churchill and Clinkenbeard 2002). Remedial approaches could include the following: (i) re-vegetation, contouring, and possibly re-location of waste piles, (ii) establishment of settling basins, (iii) routing of mine drainage or storm runoff away from, or around, mercury-rich deposits and calcines at mercury mines (Rytuba 2000), and (iv) stabilization of stream banks containing mercury-rich debris. Mercury-enriched liquids include geothermal fluids and ground water that has been in contact with contaminated mine wastes. Geothermal fluids contribute very little mercury to watershed runoff in the Bay-Delta ecosystem, relative to eroding mine wastes (Churchill and Clinkenbeard 2002).

Settling basins could be constructed to trap mercury-rich precipitates at geothermal sites, but containment of mercury in geothermal fluids may not be cost effective. Reducing mercury mobilization by soil and ground waters could be accomplished by routing surface runoff away from waste piles and possibly by the use of geo-membranes to retard infiltration.

(3) To implement pilot remediation projects. After completion of objectives 1 and 2 above, pilot projects should be implemented to examine the efficacy of various remedial approaches. Pilot projects conducted at "type" locations could be useful for "scaling up" predictions of reductions in mercury loads at the basin scale, given more intensive remedial efforts. Pilot remediation sites should be representative of "type conditions" (e.g., mine waste piles susceptible to erosion, unstable stream bank deposits near mines, geothermal springs, mine sites discharging into mercury-sensitive areas, mine sites mixed with acid mine drainage, reservoir oxygenation projects, sulfate control projects). Pilot projects should be designed to allow testing of hypotheses related to factors controlling the response to remediation (e.g., slope, grain size, mercury concentration, vegetation cover). To the extent feasible, pilot projects should be linked to other CALFED investigations, including monitoring of mercury in sentinel fishes, assessment of mass balances for total mercury and methylmercury, and process studies of mercury cycling.

(4) To identify non-mercury targets for remediation. Factors other than bioavailable mercury, such as sulfate and organic carbon, may limit the net production of methylmercury in the Bay-Delta ecosystem. The addition of sulfate, for example, can stimulate methylation without addition of mercury (Gilmour et al. 1992, Branfireun et al. 1998), and the addition of dissolved organic carbon to experimental mesocosms in the Florida Everglades stimulated more methylmercury production than did addition of either mercury or sulfate alone (David Krabbenhoft, U.S. Geological Survey, Middleton, Wisconsin, unpublished data). Some mercury sources that do not contribute substantively to mercury loadings, but are important sources of sulfate (Churchill and Clinkenbeard 2002), may warrant careful consideration for remedial efforts.

(5) To develop and employ performance measures to evaluate the effectiveness of remedial actions. Performance measures should be developed to evaluate the success of remedial actions in reducing (i) mercury loads and (ii) bioaccumulation of methylmercury. Such performance measures could be quantified at various locations down-gradient from remedial sites to estimate the spatial extent of benefits from remedial actions, given that some sites may contribute a small fraction of the mercury load at the basin scale and that benefits would be most evident near the site of remediation. Moreover, priority should be placed on assessing the effects of remedial actions on the abundance of methylmercury, which better reflects the overall goal of source remediation. Performance measures related to bioaccumulation could be accomplished by coordinating sampling and analysis with the monitoring of mercury in sentinel species (core component 4), and should be quantified at various spatial scales.

3. Quantification of Effects of Ecosystem Restoration on Methylmercury Exposure

The *overall management goal* of this core component is to document and understand the effects of restoring wetland and floodplain habitats on the production and bioaccumulation of methylmercury in the Bay-Delta ecosystem. Success in achieving this goal will require an understanding of processes and factors that affect the methylation of inorganic mercury and the demethylation of methylmercury, an understanding of the causal linkages between restoration activities and these mercury transformations, and a knowledge of pathways involved in the entry of methylmercury into aquatic food webs.

This core component focuses on those restoration activities, particularly wetland restoration and floodplain restoration and inundation, with the greatest perceived potential to increase the production and bioaccumulation of methylmercury. Wetland restoration is emphasized, because the areal extent of planned wetland restoration in the Bay-Delta ecosystem is large (CALFED Bay-Delta Program 2000*b*) and restored wetlands may become increasingly significant as sites of methylmercury production and export (Hurley et al. 1995, St. Louis et al. 1996, Sellers et al. 2001). This core component includes the following objectives.

(1) To characterize the biogeochemical cycling of mercury in wetlands, with emphasis on understanding processes and factors controlling the abundance of methylmercury. Process-level investigations of mercury cycling should examine methylation and demethylation in wetlands, and identify pathways for the transport and entry of methylmercury into food webs supporting production of fish and wildlife. This work is needed to identify environmental and trophic (or food-web) factors controlling the net production of methylmercury and the resulting exposure of biota across wetland types in the Bay-Delta system. These studies should identify ecosystem changes resulting from restoration activities (e.g., altered soil and water chemistry, water flow, hydroperiod, and food webs) and determine how such changes affect the production and bioaccumulation of methylmercury, given that a mechanistic understanding is needed for ecosystem management. Relevant indicators of methylmercury production and biotic exposure in wetlands should also be developed. Investigations should be done at multiple spatial scales to assess the extent to which wetland restoration influences the abundance of methylmercury at both local and ecosystem scales.

(2) To determine if the net production of methylmercury and biological exposure to methylmercury vary among existing types of wetlands. Investigations should quantify and compare the net production of methylmercury and biological exposure to methylmercury in existing types of wetlands (agricultural, managed, tidal, and non-tidal) within the Bay-Delta system. Food-web structure, which can greatly affect methylmercury exposure in biota of upper trophic levels, should also be characterized. The information obtained should be entered into a geospatial database to facilitate the qualitative ranking of wetland types, sub-habitats, and geographic settings with respect to methylmercury supply and associated biotic exposure. This work should support the eventual development of a conceptual model of methylmercury bioaccumulation versus wetland type that can be used to guide restoration planning.

(3) To document the effects of wetland restoration activities on the abundance and distribution of methylmercury by incorporating process-based investigations and analyses of biosentinel species into restoration projects. Process-level investigations should examine mercury transformations that influence the abundance of methylmercury and quantify the comparative bioaccumulation and trophic transfer of methylmercury in areas affected and unaffected by wetland-restoration projects. Spatiotemporal variations in methylmercury concentrations in biosentinel species, coordinated with the monitoring of mercury in fish (core component 4), should be statistically examined to assess their relation to ecosystem restoration activities.

(4) To estimate the cumulative contribution of restored wetland and floodplain habitats to the total methylmercury budget for the Delta and Bay. The internal, systemic production of methylmercury in all restored areas should be estimated and compared to the external methylmercury budget for the Bay-Delta System. Wetlands may be important sites of methylation, but do they contribute significantly to methylmercury budgets at the scale of the whole ecosystem? This effort should be an iterative process, and estimates should be refined as quantification of external and internal methylmercury production improves.

Some restoration activities (channel reconstruction and dam removal) and remedial efforts (reduction in loadings of mercury and fine sediment) are expected to affect the transport and distribution of sediment and associated (mostly inorganic) mercury. This core component, however, does not emphasize the effects of restoration on the distribution and transport of total mercury in the ecosystem. Load reduction is addressed in core components 1 and 2, and potential effects of dam removal are being addressed in CALFED investigations in the Upper Yuba River Studies Program.

With regard to evaluating potential effects of ecosystem restoration on mercury cycling, we recommend that highest priority be given to investigations examining effects of restoration on (1) the bioavailability of inorganic mercury for methylation and (2) the microbial production of methylmercury. Mercury contamination of aquatic environments is widespread in the Bay-Delta ecosystem. We believe that changes in bioavailability or methylation rates have much greater potential to significantly increase methylmercury exposure in this ecosystem than do changes in the spatial distribution of total (mostly inorganic) mercury. Studies in other aquatic ecosystems show that experimental stimulation of methylation can increase the abundance of methylmercury and its uptake in biota by 10- to 20-fold, even in lightly contaminated environments where no mercury was added (Kelly et al 1997, Bodaly et al. 2002).

4. Monitoring of Mercury in Fish, Health-Risk Assessment, and Risk Communication

The consumption of fish and other aquatic organisms is the primary pathway for human exposure to methylmercury. A regional program for monitoring mercury concentrations in fish should, therefore, be in effect during ecosystem restoration. The *first management goal* of the monitoring program would be to protect human health by providing informed guidance for reducing dietary exposure to methylmercury, the dominant form of mercury in fish. The *second management goal* of the monitoring program would be to provide a "performance measure" to gage methylmercury contamination of the Bay-Delta ecosystem.

Goal 1, the protection of human health, should include the following objectives.

(1) To monitor concentrations of total mercury (present largely as methylmercury) in sport fish eaten by humans. Monitoring should identify fish, shellfish, and other aquatic biota consumed by humans that contain mercury concentrations exceeding criteria for protection of human health. Monitoring should also identify fish with low concentrations that can be safely eaten.

(2) To assess health risks of fish consumption to humans. This objective would be facilitated by the development of an effective data management system for storage and retrieval of data on mercury in fish, shellfish, and other edible aquatic biota.

(3) To provide fish-consumption advice to the public. Fish-consumption advisories can be effective for reducing exposure of humans to methylmercury. Existing and monitoring data should be analyzed to determine if a single regional fish-consumption advisory is appropriate or whether spatial variation in contamination of fish warrants multiple advisories across the region.

(4) To transfer information through public outreach. The public benefits of this program would be enhanced by active public outreach and by communication of findings to environmental health professionals. Monitoring data, combined with information from special studies, can be used to identify priority areas and target groups for outreach and education efforts, which should also communicate the health benefits of eating clean fish.

(5) To perform special studies needed to support health-risk assessment and risk communication. Ancillary studies may be needed to estimate rates and patterns of fish consumption, to identify and characterize groups with potentially high levels of exposure, to identify optimal methods for communicating advice, and to evaluate the effectiveness of fish-consumption advisories.

Goal 2 of this core component, to gage methylmercury contamination of the ecosystem, would provide a performance measure for ecosystem restoration. Many factors can influence the bioaccumulation of methylmercury in long-lived biota of upper trophic levels, greatly complicating the detection and interpretation of patterns in mercury concentrations in large game fishes. A biosentinel-based monitoring approach is, therefore, preferable for gaging methylmercury contamination of aquatic food webs and for detecting spatial and temporal patterns in contamination during restoration.

A biosentinel species should possess certain key attributes. It should be spatially widespread and abundant throughout much of the ecosystem. Ecotoxicological relevance is enhanced if the biosentinel is important in the diets of certain piscivores and substantially involved in the food-web transfer of methylmercury. The biosentinel should exhibit limited variation in diet and trophic position; in other words, variation in mercury concentrations in the biosentinel should result largely from variation in processes influencing the abundance of methylmercury in the aquatic ecosystem, rather than to differences in diet or trophic position. Small whole fish, such as 1-year-old yellow perch (*Perca flavescens*), have been widely used as a biosentinel of methylmercury contamination of food webs in temperate lakes in the United States and Canada (Frost et al. 1999, Wiener et al. 2003). During their first year, yellow perch occupy a low trophic position, feeding on zooplankton and small zoobenthos, yet small yellow perch are regionally important in methylmercury transfer in food webs supporting sport fish, piscivorous wildlife, and humans who consume sport fish. Age-1 perch are also sensitive indicators of annual and spatial variation in the abundance of methylmercury in aquatic food webs (Frost et al. 1999). Young-of-the-year fish may also be useful as a biosentinel.

Goal 2 should include the following two objectives.

(6) To monitor total mercury in biosentinel species to assess methylmercury contamination of aquatic food webs. Sampling and analyses of biosentinel fishes (or other aquatic biota) would provide a direct measure of methylmercury concentrations in aquatic food webs supporting production of piscivorous fish and wildlife.

(7) To identify spatial and temporal patterns in mercury concentrations in bioindicator fishes. Spatiotemporal patterns in mercury contamination of biosentinel fishes should be statistically examined to assess their possible relation to ecosystem restoration activities or other potential causal factors. The sampling design should, therefore, include monitoring sites in the vicinity of wetland restoration projects.

Monitoring data would not – in the absence of other supporting information – conclusively demonstrate cause-and-effect associations. The interpretation of data from a monitoring program should be strengthened by linking monitoring efforts to investigations of ecological and biogeochemical processes or factors that affect the abundance of methylmercury, as well as its bioaccumulation and trophic transfer in aquatic food webs.

5. Assessment of Ecological Risk

Methylmercury is a potential threat to organisms in upper trophic levels of aquatic food webs in mercury-contaminated ecosystems. In birds and mammals, methylmercury in reproducing females readily passes to the developing egg or embryo, and the early developmental stages are much more sensitive than the adult to methylmercury exposure (Scheuhammer 1991, Wiener et al. 2003). Avian reproduction can be impaired in females fed diets with concentrations of methylmercury that are one-fifth of the threshold dietary concentrations causing overt toxicity in adult birds of the same species (Scheuhammer 1991).

A number of bird species that nest or feed in the Bay-Delta may be sensitive to methylmercury exposure (Heinz 2002, Schwarzbach and Adelsbach 2002). Concentrations of total mercury (probably present as methylmercury) in six failed eggs of the federally endangered clapper rail, taken from the central San Francisco Bay, averaged 0.81 µg/g wet weight and ranged from 0.60 to 1.06 µg/g (Schwarzbach and Adelsbach 2002). Methylmercury concentrations of 0.8 µg/g wet weight or greater in eggs adversely affected embryo survival in controlled, egg-injection experiments with eggs of clapper rails (Heinz 2002). Diminished reproductive success could have adverse population-level consequences for clapper rails and other species of wildlife and fish exposed to high levels of methylmercury in the Bay-Delta ecosystem.

The decision process for adaptive restoration of the Bay-Delta System will require information on methylmercury exposure and associated ecological effects in fish and wildlife. Estimates of exposure thresholds associated with reproductive effects in species of concern, based on methylmercury concentrations in tissues or the diet, are currently lacking but would provide biologically relevant targets applicable to adaptive management and environmental decisions. Information in exposure thresholds could also be used to identify those species that are most vulnerable to methylmercury (in terms of sensitivity and exposure) and to assess whether existing levels of methylmercury exposure in the ecosystem could impair recovery of at-risk native species.

The *overall science goal* for this core component is to quantify methylmercury exposure and to assess the likelihood that adverse ecological impacts are occurring or may occur in fish and wildlife as a result of methylmercury exposure. The *overall management goal* is to protect fish and wildlife from adverse effects of methylmercury exposure. Success in achieving this mercury-specific management goal would directly support CALFED's strategic restoration goals concerning the recovery of at-risk native species and the rehabilitation of the Bay-Delta to support native biotic communities. To achieve this specific management goal, investigations in this core component should be linked to those in core components 2 (remediation of mercury source areas), 3 (quantification of effects of ecosystem restoration on methylmercury exposure), and 6 (identification and testing of potential management approaches for reducing methylmercury contamination). This goal should be supported by the following two objectives.

(1) *To determine the toxicological significance of methylmercury exposure in wildlife and fish, with emphasis on reproductive effects.* Evaluation of the toxicological effects of methylmercury in fish and wildlife should focus on reproductive endpoints, such as embryo survival (Heinz 2002) or spawning success (Hammerschmidt et al. 2002), because of their high sensitivity to methylmercury and relevance to assessing population-level effects. Threshold concentrations of methylmercury (in the tissues or diet) associated with impaired reproduction or other adverse effects in developing young should be estimated.

Dose-response relations and threshold concentrations for reproductive effects should be estimated with controlled laboratory experiments, such as egg-injection experiments for birds (Heinz 2002). Field studies of wildlife should quantify methylmercury exposure in a range of habitat and restoration settings in the Bay and Delta. New and existing dose-response information from experimental studies should be compiled to develop an adequate data base for extrapolation to a variety of pertinent native species in the Bay-Delta System. For birds, information from the laboratory and field studies by Heinz (2002) and Schwarzbach and Adelsbach (2002) should be used to select species and populations for further investigation. Field and laboratory investigations should be closely linked. The species used in laboratory experiments should match those studied in the field, and the range of methylmercury exposures in laboratory studies should include the range observed in the Bay-Delta ecosystem.

Information on the combined effects of methylmercury and selenium may be needed to fully assess reproductive effects of contaminant exposure in the Bay-Delta ecosystem, which is also contaminated with selenium. Adverse reproductive effects on developing mallard embryos exposed experimentally to methylmercury via the maternal diet, for example, were much greater when selenomethionine and methylmercury were administered jointly than when methylmercury was added without selenium (Heinz and Hoffman 1998).

(2) To identify habitats, areas, and trophic pathways associated with elevated, potentially harmful methylmercury exposure. Habitats, areas, and trophic pathways in the Bay and Delta that are associated with the bioaccumulation and biomagnification of methylmercury to elevated, potentially harmful concentrations should be identified. For birds, the information from recent studies by Heinz (2002) and Schwarzbach and Adelsbach (2002) could be used to select species, populations, and associated foraging sites for investigation. This work should focus largely on evaluating pathways of methylmercury exposure in at-risk, native species of fish and wildlife that are of special concern to resource managers. Bioaccumulation in species of special concern should be linked to sources of methylmercury in field settings, to identify dietary sources of methylmercury and trophic pathways, habitats, and areas associated with high organismal exposure to methylmercury. Habitats and areas associated with high methylmercury exposure should be identified, characterized, and prioritized with regard to ecological risk. It would be desirable to link some of this work to (already funded) process-level investigations that are

examining the microbial production of methylmercury and its entry and subsequent transfer in aquatic food webs supporting production of fish and wildlife.

6. Identification and Testing of Potential Management Approaches for Reducing Methylmercury Contamination

The *overall management goal* of this core component is to identify and evaluate potential landscape management approaches for reducing the production and abundance of methylmercury in the ecosystem, as well as the associated exposure of resident biota. Process-oriented results from core component 3 (Quantification of Effects of Ecosystem Restoration on Methylmercury Exposure) and other mercury investigations studies should be used to identify potential landscape management approaches for consideration. Specific objectives needed to achieve this goal are as follows.

(1) To develop an empirical understanding of processes and habitat factors affecting methylmercury production and exposure. This work should focus on wetlands and tidal flats in the Bay and Delta and should use information from other ecosystem investigations in conjunction with information from the Bay and Delta (from core component 3).

(2) To develop models for predicting effects of specific management scenarios on methylmercury production and export. Initial models could be based on empirical information, but efforts should eventually evolve toward development of process-based, numerical models. Various model types and spatiotemporal scales should be explored, including spatially explicit landscape models. A GIS database (with new and existing data) should be developed to map, classify, and rank wetland types, sub-habitats, and geographic setting with respect to methylmercury supply and biotic exposure.

(3) To determine which of the factors controlling methylmercury production and exposure can be managed in the Bay-Delta ecosystem. This is a crucial link between management and science. What controlling factors can be realistically manipulated without unacceptable consequences? Potential management scenarios should be identified and evaluated as pertinent information becomes available. Examples of potential scenarios include the siting of marsh restorations, the control or diversion of mercury and sediment loads (especially from sources with high bioavailability), and the alteration of vegetation or water flow and hydroperiod. The potential utility of such manipulations should be initially considered in relation to logistical feasibility, cost, potential decreases in methylmercury production, and effects on habitat quality.

(4) To test candidate landscape management approaches in pilot studies to assess performance with regard to methylmercury production and biotic exposure. Potential landscape-management approaches should be tested to assess performance. Initial experimental manipulations could be done at the mesocosm scale. To the extent feasible, larger scale tests should be linked to ongoing process studies and to monitoring of biosentinel organisms to evaluate performance.

Linkages and Integration among Core Components

The mercury strategy, as outlined here, is an integrated program with strongly interconnected components (Figure 4). The interactions include linkages between scientific activities (research and monitoring) and linkages between scientific investigations and management actions (risk communication, source remediation, ecosystem restoration, and landscape management). The evaluation of outcomes is also an important feature of the strategy. Scientific investigations, management actions, and evaluations within a given core component should be strongly linked, and these activities should be continuous, rather than sequential. These linkages, which form the basis for adaptive management of mercury in the ecosystem, are utterly crucial for meeting the goals and objectives outlined for the strategy and for providing timely scientific input for adaptive management. The authors of this document contend that the scientific merit, rigor,

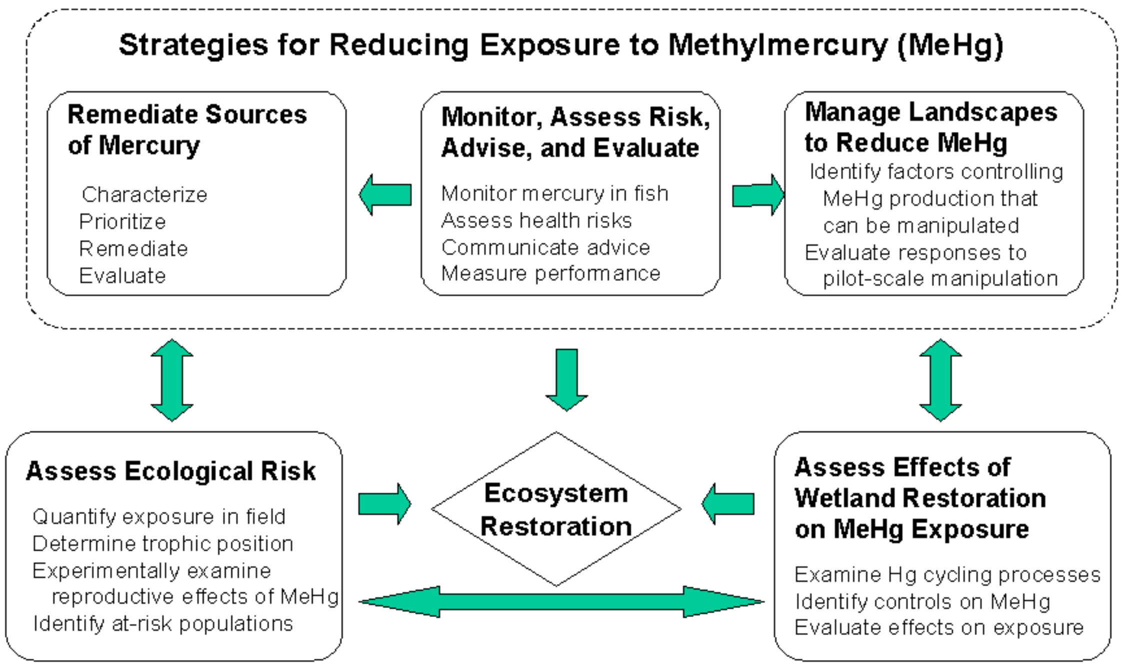

Figure 4. Conceptual model of linkages among components of the mercury strategy. Arrows represent linkages among components of the strategy, where information should flow to provide adaptive feedback for refinement of both scientific and management actions. For simplification, strategy components 1 and 2 (both related to mercury sources) were combined into the single cell on the upper left-hand corner of the figure.

cost-effectiveness, and overall worth of a mercury program in the Bay-Delta ecosystem will increase in proportion to the strength of such linkages.

The linkages among core components of the mercury strategy are illustrated in Figure 4, where shaded arrows represent the flows of information and interactions that are needed to support decision processes for refinement of scientific investigations and for adaptive management of mercury in the ecosystem. Science is an integral and ongoing tool in adaptive restoration and management; new information gaps will arise as existing gaps are filled, and ongoing evaluation is a key element of adaptive management.

VI. Management of a Mercury Science Program

The global scientific effort on mercury has produced rapid advances and several landmark discoveries in the past decade (Wiener et al. 2003). Recent scientific progress in the Bay-Delta ecosystem has also been substantial (Stephenson et al. 2002), and increasingly powerful analytical tools and approaches are becoming available for addressing scientific and management questions concerning mercury in the ecosystem. A CALFED mercury program would catalyze substantive advances in understanding of mercury cycling and its effects in the Bay-Delta ecosystem, an ecosystem of national importance and renown. The decision-making arena for management and restoration of this ecosystem is expected to be rigorous, and funded projects should meet high standards of reliability, scientific defensibility, and productivity.

The impressive recent progress notwithstanding, critical information gaps remain and much of substance needs to be learned regarding the behavior of mercury in this ecosystem, the risks posed to resident biota and humans, and the steps that can be taken to address the problem. Mercury pollution in the Bay-Delta ecosystem represents an enormous challenge for science and ecosystem management. Managers attempting to reduce methylmercury exposure in this ecosystem must contend with a highly complex biogeochemical cycle, overlain on an ecosystem characterized by enormous complexity, large scale, and pronounced spatiotemporal dynamics. An interdisciplinary effort will be needed to implement this strategy and to apply the new information produced towards adaptive management of the Bay-Delta ecosystem. Many of the core components recommended in section V of this document will require multidisciplinary teams of scientists, as well as the sustained involvement of the appropriate environmental planners and resource managers.

Recommended Approaches for Allocation of Program Funding

Competitive Proposal Review and Selection Process. The competitive Proposal Solicitation Package process used by CALFED is an appropriate mechanism for allocating scientific effort to most of the core components of the mercury strategy outlined in section V of this document. An exception is the core component “Monitoring of Mercury in Fish, Health-Risk Assessment, and Risk Communication,” for which the competitive proposal process is not considered optimal. The competitive proposal process would, however, be appropriate for one part of the mercury monitoring program; that is the special studies needed to support health-risk assessment and risk communication (goal 1, objective 5). Detailed recommendations for developing an effective monitoring program are presented in the next subsection.

Requests for proposals should encourage the development of collaborative interdisciplinary proposals by multi-institutional teams of investigators. In addition to judging scientific merit and relevance to ecosystem management, the proposal review and selection process should include critical evaluation of the scientific stature, leadership skills, and managerial experience of the leading principal investigator (and project manager, if applicable) on prior large projects, as well as the experience and effectiveness of co-investigators as team members on large multidisciplinary projects. The roles and responsibilities of individual team members should be clearly described in project proposals. Team members should have demonstrated skill and expertise in their individual areas of technical responsibility on the proposed work, as well as a track record of timely reporting of findings in refereed papers with coauthors from multiple institutions.

The proposal evaluation process should also include critical evaluation of the composition of project teams. Other large "mercury" research programs have shown that an interdisciplinary approach is essential for understanding the effects and behavior of mercury at the ecosystem scale. Project teams should contain the full range of expertise needed to ensure defensible study design, analyses, and interpretation of data. We recommend that, on average, about half of the team members on a project be "mercury specialists" and the remainder be scientists who bring other, appropriate expertise and knowledge on ecosystem processes (e.g., hydrology, microbial ecology, biogeochemistry, trophic ecology), organismal biology, wetland ecology, sampling design, statistical analysis, modeling, or other pertinent applications. It is essential that mercury specialists work in collaboration with scientists and managers who are knowledgeable about the Bay-Delta ecosystem. Projects estimating mass budgets for mercury or other material constituents in the tidally influenced Bay-Delta, for example, should involve hydrodynamic specialists in the design of sampling strategies. Scientific projects should also involve external scientists who can bring new perspectives, approaches, and analytical capabilities to the team, such as the use of stable-isotope techniques (Hintelmann et al. 2002) to examine the cycling of mercury in the Bay-Delta ecosystem.

Project proposals should demonstrate earnest commitments by team leaders and key team members to provide timely information to ecosystem managers and to participate actively in the application of project results to adaptive management of the ecosystem. Beyond the project level, proposals should reflect a willingness by lead investigators to participate substantively in interdisciplinary syntheses of findings from multiple projects. Project budgets should delineate and include the estimated costs for time and travel associated with such efforts.

Development of a Monitoring Program for Mercury. The establishment of a systemic monitoring program for mercury in fish was considered a high-priority goal by scientists and managers alike. The development and design of an effective monitoring program – capable of achieving multiple objectives (section V, core component 4) – will be a substantial endeavor, requiring insightful leadership, input from managers, multidisciplinary technical guidance, and modest budgetary support. The Proposal Solicitation Package process used by CALFED is not an optimal approach for developing a monitoring program for mercury in Delta fishes. We recommend that a monitoring program be developed in a step-wise fashion, as outlined below, with informed input from leading scientists, managers, and end-users of the monitoring data along the way.

(1) *Establish a multidisciplinary, multi-institutional steering committee to lead and facilitate the developmental process* – This steering committee should include representatives of appropriate management, regulatory, and scientific groups.

(2) *Refine goals and objectives* – Refinement of the goals and objectives identified at the mercury strategy workshop (summarized in Section V, core component 4) is an essential early

step in development, needed to ensure that the monitoring program is designed at the onset to address the information needs of management entities, regulatory agencies, and other end users. Informal peer review of refined goals and objectives is strongly encouraged at this stage.

(3) *Develop robust sampling strategies* – Statistical expertise in sampling design and statistics should be applied to develop robust sampling strategies capable of meeting defined objectives. Statistical analyses of recent, reliable fish-mercury data should be used in crafting an efficient sampling design.

(4) *Develop detailed procedures for program tasks* – Protocols should be developed for each of the following: sampling of fish, handling and analyses of samples, quality assurance and quality control, archiving of samples (if warranted), management of data, statistical analysis of data, synthesis and reporting of information, public outreach, and periodic peer review of all aspects of this core component by an expert panel.

(5) *Subject the sampling frame, methods, and detailed procedures to external peer review and incorporate appropriate revisions*.

(6) *Issue contracts to accomplish program tasks* – This work should be contracted to a scientific team that is experienced in the sampling and analysis of fish for mercury, with proven capabilities in the management, statistical analysis, and rigorous interpretation of large data sets and a track record of timely reporting of findings from large multidisciplinary projects on mercury. Moreover, the team members should have the institutional support needed for a sustained commitment to at least a 4-year monitoring program. Contracts should be issued with minimal delay to allocate funds for initiating and accomplishing program tasks.

Fiscal support for steps 1-5 above should be provided by CALFED. The provision of in-kind support from involved state and federal agencies in all aspects of development and execution is encouraged throughout the monitoring program.

The monitoring program should be adaptive, with the flexibility to evolve in response to new knowledge and the changing needs of management and regulatory entities. In this regard, the steering committee is encouraged to consider the operational structure and process used in managing the Regional Monitoring Program for the Bay, an adaptive program with annual funding of about $3 million, as a model for managing this new monitoring program. After initial program development, the steering committee's role could include (1) the facilitation of communication between managers and scientists, (2) consideration of proposed modifications to increase program efficiency and to ensure responsiveness to the evolving needs of information users, and (3) the coordination of peer reviews.

Communication, Management and Sharing of Data, and Integration of Findings

An implemented mercury program will produce large amounts of data, and open communication of data and results among participating scientists, agencies, stakeholders, and the public are vital for successful adaptive management and for sustaining political support for the program (Johnson 1999*b*). The transfer and sharing of information from ongoing investigations should be actively facilitated, given the importance of rigorous interdisciplinary interpretation and the need to provide timely information for adaptive management. The typical lag times from generation of scientific data until final reporting and publication are long, relative to the anticipated rapid pace of scientific discovery and generation of new information in a mercury program of this scale. Effective mechanisms for rapid sharing of interim results among teams and for information transfer to managers, other stakeholders, and the public will be essential to ensure that interim data and information are available to facilitate timely information synthesis, risk analysis, and risk communication. To encourage the exchange of interim results, it is recommended that ground rules be developed for the sharing of data among teams and for the public release of data and findings. We recommend that interim data and products be summarized on a protected website and that listings of existing and forthcoming products be maintained to facilitate the synthesis of findings among teams.

An annual meeting of investigators and ecosystem managers should be convened to provide a forum for sharing of data and interpretations, as well as discussion, formulation of manuscript plans, and integration of interim results. A review of funded mercury investigations should be a key feature of the annual meeting. It is recommended that an external science review panel with at least five renowned specialists be established at the beginning of the funding period to serve throughout the anticipated, 4-year effort. The panel should be technically diverse, with the collective ability to critically evaluate work in each of the following topical areas: microbial ecology, ecology and hydrodynamics of estuarine ecosystems, biogeochemistry and ecology of wetlands, environmental biogeochemistry of mercury, bioaccumulation and ecotoxicology of mercury, risk analysis, and risk communication. The external review process should provide critical evaluations at both the project and multi-project (mercury program) levels. Another, less structured meeting could be convened annually to coordinate future work among teams. Much routine communication and information exchange can be facilitated with electronic bulletin boards and web sites.

Several participants at the mercury strategy workshop expressed a desire for a formal process of communication among scientists, engineers, and managers to implement adaptive management (Appendix 2). Such a process could link decisions on ongoing restoration efforts to information from ongoing or recently completed investigations. Moreover, it was suggested that resource agencies involved with species of concern, restoration of fisheries, sediment supply, water quality, land use, water management, and reuse of dredged sediments participate in the process.

Quality Control and Quality Assurance

Program Level. Procedures for programmatic oversight of quality assurance should be in place at the onset of a funded mercury program to define the comparability of data from the participating research groups and to aid responsible use of the information by managers and stakeholders. Quality assurance is particularly important in a mercury program, because of the overall difficulty in accurately quantifying relevant species of mercury, especially methylmercury, in dilute media with concentrations at the sub-nanogram per liter (part-per-trillion) level. Institutionalized oversight at the program level is needed to address two quality-assurance challenges: (1) to establish confidence that the data produced by multiple laboratories are comparable, and (2) to demonstrate the validity of data for future use and interpretation.

There are many potential components to a robust quality control and quality assurance program, including inter-laboratory comparisons (blind, round-robin exchange of samples), analyses of split samples from the field, on-site laboratory assessments, estimation of method detection limits, validation of data by third parties, and technical review of methods used for the handling, preparation, and analyses of samples. Inter-laboratory comparisons, which are particularly useful for documenting inter-laboratory precision, should be conducted annually or biannually for the duration of the project. Blind Certified Reference Materials can be used in inter-laboratory comparisons to document and quantify both precision and accuracy (bias). An effective, quality-assurance program enhances the confidence of participating research teams and provides quantitative documentation of the precision, accuracy, comparability, and representativeness of the data collected. About 5 to 10 percent of the annual analytical workload in a project should be devoted to quality assurance at the programmatic level.

Project level. The effort devoted to quality control and quality assurance at the project level should exceed that done at the program level. Quality control and quality assurance activities should be designed to evaluate both field and laboratory methods. Project-level procedures or material to be evaluated should include the collection, handling, preservation, and preparation of samples, as well as chemical reagents, instrumentation, analyses, and documentation. About 25 to 35 percent of the total analytical workload in a project (including field replicates and laboratory splits of samples) should be devoted to quality assurance at the project level.

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Appendix 1. Agenda for the first mercury workshop, which included (1) the final review of the CALFED Project "An Assessment of Ecological and Human Health Impacts of Mercury in the Bay-Delta Watershed," (2) descriptions of two future mercury projects to be funded by CALFED, and (3) discussion of the Mercury Strategy for the Bay-Delta System and Watershed.

Final Workshop Agenda

Monday, September 16 and Tuesday, September 17, 2002
Moss Landing Marine Laboratories, Main Seminar Room
8272 Moss Landing Road, Moss Landing, CA

Monday, September 16

8:00 Registrant Sign In

8:30 Welcome and Introductions. Kenneth Coale, Director, Moss Landing Marine Laboratories

8:40 Goals of the Workshop. Scientific Review Committee

Summary Presentations of Findings from the CALFED Project "An Assessment of Ecological and Human Health Impacts of Mercury in the Bay-Delta Watershed"

9:00 Synthesis of Delta Studies. Gary Gill, Texas A&M University (Galveston, TX), Steve Schwarzbach, USGS (Sacramento, CA), Kenneth Coale and Mark Stephenson, Moss Landing Marine Laboratories (Moss Landing, CA), Chris Foe, Central Valley Regional Water Quality Control Board (Sacramento, CA), Darell Slotton, University of California (Davis, CA), Gary Heinz, USGS (Laurel, MD), and Jay Davis, San Francisco Estuary Institute (Oakland, CA)

9:30 Mercury Mass Balance for the Freshwater Sacramento-San Joaquin Bay-Delta Estuary. Chris Foe, Central Valley Regional Water Quality Control Board (Sacramento, CA)

10:00 Sediment-Water Exchange and Estuarine Mixing Fluxes in the San Francisco Bay-Delta Watershed. Gary Gill, Texas A&M University (Galveston, TX)

10:45 Assessment of Methyl and Total Mercury in Delta Sediment. Wes Heim, Kenneth Coale and Mark Stephenson, Moss Landing Marine Laboratories (Moss Landing, CA)

11:15 Effects of Wetland Restoration on the Production and Bioaccumulation of Methyl Mercury in the Sacramento San Joaquin Delta, California. Darell Slotton, Shaun Ayres, Tom Suchanek, Ronald Weyland, Anne Liston, Chance MacDonald, Douglas Nelson, and Brenda Johnson, University of California (Davis, CA)

11:45 Mercury in Sport Fish From the Delta Region. Jay Davis and Ben Greenfield, San Francisco Estuary Institute (Richmond, CA), Gary Ichikawa and Mark Stephenson, Moss Landing Marine Laboratories (Moss Landing, CA)

1:00 Pilot Transplant Studies with the Introduced Asiatic clam, *Corbicula fluminea*, to Measure Methyl Mercury Accumulation in the Sacramento-San Joaquin Delta Estuary. Chris Foe and Stacy Stanish, Central Valley Regional Water Quality Control Board (Sacramento, CA), Mark Stephenson, Moss Landing Marine Laboratories and California Department of Fish and Game (Moss Landing, CA)

1:30 Laboratory Assessment of the Hazards of Mercury to Reproduction in Aquatic Birds. Gary Heinz, USGS (Laurel, MD)

2:00 Field Assessment of Mercury Exposure in Aquatic Birds in the Bay-Delta Ecosystem. Steve Schwarzbach, USGS (Sacramento, CA) and Terry Adelsbach, USFWS (Sacramento, CA)

2:30 Conceptual Model of Hg in Cache Creek. Charles Alpers, and Joe Domagalski, USGS (Sacramento, CA), Darell Slotton, Thomas Suchanek, and Shaun Ayers , University of California (Davis, CA), Nicolas Bloom, Frontier Geosciences (Seattle, WA), and Ronald Churchill and John Clinkenbeard, California Division of Mines and Geology (Sacramento, CA)

2:35 Mercury and Methylmercury Concentrations and Loads within the Cache Creek Watershed, California, January 2000 through May 2001. Joe Domagalski and Charles Alpers, USGS (Sacramento, CA), Darell Slotton, Thomas Suchanek, and Shaun Ayers, University of California (Davis, CA)

3:20 Mercury Bioaccumulation and Trophic Transfer in the Cache Creek Watershed, California, in Relation to Diverse Aqueous Mercury Exposure Conditions. Darell Slotton, Shaun Ayers, Thomas Suchanek, Ronald Weyand, and Anne Liston, University of California (Davis, CA)

3:50 Mercury Loading and Source Bioavailability from the Upper Cache Creek Mining Districts. Thomas Suchanek, USFWS (Sacramento, CA) and University of California (Davis, CA), Darell Slotton, Douglas Nelson, Shaun Ayers, Chance Asher, Ron Weyand, Anne Liston, and Collin Eagles-Smith, University of California (Davis, CA)

4:20 Solid Phase Mercury Speciation and Incubation Studies in or Related to Minesite Runoff in the Cache Creek Watershed. Nicolas Bloom and Eve Preus, Frontier Geosciences, Inc. (Seattle, WA)

4:50 Assessment of the Feasibility of Remediation of Mercury Mine Sources in the Cache Creek Watershed. Ronald Churchill and John Clinkenbeard, California Division of Mines and Geology (Sacramento, CA)

5:20 Engineering Evaluation and Cost Analysis of Alternatives to Remediate the Sulfur Creek Mercury District, Colusa and Lake Counties, California. Greg Reller, TetraTech (Sacramento, CA)

5:50 Synthesis of Cache Creek Studies. Joe Domagalski and Charles Alpers, USGS (Sacramento, CA), Darell Slotton, Thomas Suchanek and Shaun Ayers , University of California (Davis, CA), Nicolas Bloom, Frontier Geosciences (Seattle, WA), and Ronald Churchill and John Clinkenbeard, California Division of Mines and Geology (Sacramento, CA)

Tuesday, September 17

8:00 Open Discussion of Project Results and Hypotheses from "An Assessment of Ecological and Human Health Impacts of Mercury in the Bay-Delta Watershed." Moderated by Scientific Review Committee

10:15 Direct Measurement of Microbial Mercury Cycling in Sediments of the San Francisco Bay-Delta. Mark Marvin-DiPasquale and Jennifer Agee, USGS (Menlo Park, CA)

Summary Descriptions of Two Future Mercury Projects to be funded by CALFED

10:45 Transport, Cycling, and Fate of Mercury and Monomethyl Mercury in the San Francisco Delta and Tributaries: An Integrated Mass-Balance Assessment Approach. Kenneth Coale, Moss Landing Marine Laboratories (Moss Landing, CA)

11:20 Evaluation of Mercury Transformations and Trophic Transfer in the San Francisco Bay/Delta: Identifying Critical Processes for the Ecosystem Restoration Program. Mark-Marvin DiPasquale, USGS (Menlo Park, CA)

Discussion of the Mercury Science Strategy for the Bay-Delta System and Watershed

1:00 Mercury in the Environment: Key Findings from Other Ecosystem Studies and their Implications for the Bay-Delta System and Watershed. Cynthia Gilmour, Academy of Natural Sciences, Estuarine Research Center (St. Leonard, MD), and David Krabbenhoft, USGS (Middleton, WI)

2:00 Development of the Mercury Science Strategy: Conceptual Framework, Constraints, and Goals. Jim Wiener, University of Wisconsin-La Crosse (La Crosse, WI)

2:30 Public Input on the Mercury Science Strategy. Open Discussion

5:00 Adjourn

Appendix 2. Agenda for the second mercury workshop, which focused on obtaining public input for development of the Mercury Strategy.

Final Workshop Agenda

Mercury Science Strategy for the Bay-Delta System and Watershed

Tuesday, October 8, and Wednesday, October 9, 2002
Moss Landing Marine Laboratories, 8272 Moss Landing Road
Moss Landing, California

TUESDAY, October 8

7:30 am	Registrant Sign In
8:00 am	Welcome and Opening Remarks. Sam Luoma, CALFED Science Program
8:10 am	Objectives of the Workshop. Jim Wiener, University of Wisconsin-La Crosse, La Crosse, Wisconsin

Session 1: The Bay-Delta Ecosystem–Characteristics Relevant to the Cycling of Mercury and Bioaccumulation of Methylmercury (Moderator: David Krabbenhoft)

8:25 am	Hydrodynamics of the Bay-Delta System and Watershed. Jon Burau, US Geological Survey (Sacramento, California)
9:05 am	Trophic and Community Ecology. Robin Stewart, US Geological Survey (Menlo Park, California)
9:40 am	Geoenvironmental Setting: Natural and Mining-Related Anthropogenic Sources of Mercury. Charles Alpers, US Geological Survey (Sacramento, California)

Session 2: The Bay-Delta Ecosystem–State of our Knowledge of the Cycling, Transformation, Bioaccumulation, and Effects of Mercury (Moderator: Dyan Whyte)

10:30 am	Mercury in the Bay-Delta Watersheds. Joseph Domagalski, US Geological Survey (Sacramento, California)
11:30 am	Mercury in the Bay-Delta System. Mark Stephenson, Moss Landing Marine Laboratories (Moss Landing, California)

Session 3: Key Findings from other Ecosystem-Level Mercury Investigations–Implications for the Bay-Delta System and Watershed (Moderator: Jim Wiener)

1:30 pm	Controls on Mercury Cycling in the Florida Everglades. Cynthia Gilmour, Academy of Natural Sciences, Estuarine Research Center (St. Leonard, Maryland)
2:00 pm	Mercury Experiment To Assess Atmospheric Loading in Canada and the United States, the METAALICUS Project. Reed Harris, Tetra Tech Inc. (Oakville, Ontario)
2:30 pm	Mercury Investigations in Other Estuarine Systems. Kristofer Rolfhus, University of Wisconsin-La Crosse (La Crosse, Wisconsin)

Session 4: Ecological Restoration of Wetlands in the Bay-Delta System and Watershed (Moderator: Cynthia Gilmour)

3:15 pm An Overview of Planned Restoration Activities. Lauren Hastings, CALFED Ecosystem Restoration Program (Sacramento, California)

4:15 pm Characteristics of Wetlands in the Bay-Delta System and their Relation to the Potential Production and Export of Methylmercury. Group Discussion

5:30 pm Adjourn (Meeting of Breakout-Group Leaders to Follow)

WEDNESDAY, October 9

7:30 am Registrant Sign In

Session 5: Towards a Mercury Science Strategy for the Bay-Delta System and Watershed (Moderator: Chris Foe)

8:00 am Goal, Unifying Themes, and Scope of the Strategy. Jim Wiener, University of Wisconsin-La Crosse

8:30 am Conceptual Framework for the Strategy. David Krabbenhoft, US Geological Survey (Middleton, Wisconsin)

9:30 am Framing Management Questions to Formulate a Science Agenda. Dyan Whyte, CALFED and California Regional Water Quality Control Board (Oakland, California)

Session 6: Identification of Management Questions and Goals concerning Mercury in the Bay-Delta System and Watershed

10:30 am Group Discussions

Topical Breakout Groups:
(1) Mercury Sources, Remediation, and Loadings
(2) Monitoring of Mercury in Biota, Health-Risk Assessment, and Risk Communication
(3) Bioaccumulation and Ecological Risk Assessment
(4) Wetland Restoration and Methylmercury Exposure

Session 7: Identification of Critical Information Gaps concerning Mercury in the Bay-Delta System and Watershed

1:30 pm Group Discussions (same topical breakout groups as in Session 6)

Session 8: Formulation of Goals, Objectives, and Priorities for Mercury Investigations in the Bay-Delta System and Watershed

3:30 pm Group Discussions (same topical breakout groups as in Sessions 6 & 7)

5:15 pm Summary Reports of Breakout-Group Leaders (large conference room)

6:15 pm Next Steps in Development of the Strategy. Jim Wiener, University of Wisconsin-La Crosse

6:30 pm Adjourn

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